ADDENDUM A
LIGHT NONAQUEOUS PHASE LIQUID EVALUATION FIELD SAMPLING PLAN
LENZ OIL SITE
LEMONT, ILLINOIS

FIELD SAMPLING PLAN
ADDENDUM A
LENZ OIL SERVICE, INC. SITE
LEMONT, ILLINOIS

REVISION: 4

JUNE 27, 1994

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1.0 INTRODUCTION

This Addendum to the Lenz Oil Field Sampling Plan (FSP) was prepared by Environmental Resources Management-North Central, Inc. (ERM-North Central) on behalf of the Lenz Oil Participating Respondents and describes the procedures for evaluating the potential presence of nonaqueous phase liquid (NAPL) at the site. A preliminary evaluation of the costs of remediating the site, presented to the USEPA on March 14, 1994, showed that some of the alternatives could be more or less expensive than others depending on the total volume of NAPL at the site. This evaluation is being conducted because of concerns raised by the U.S. Environmental Protection Agency (USEPA) regarding the extent, thickness, and characteristics of the NAPL.

The site is relatively small, 4.9 acres in total. Thus, a total of 22 piezometers will be installed at the locations shown in Figure 1. The purpose of the piezometers is to determine if any NAPL is present at those locations. The NAPL will be characterized by collecting and analyzing samples of the NAPL for the parameters presented in Section 4.2. The choice of which of the piezometer samples will be characterized will be decided, after consultation with the USEPA and the Illinois Environmental Protection Agency (IEPA), to provide a reasonable assurance (based on the thickness and distribution of NAPL), that the number of samples will be sufficient to characterize the NAPL found at the site.

Based on the results of the Remedial Investigation (RI), there is a chance that the NAPL may not be detected because of a high water table. During the RI, a NAPL was intermittently observed in monitoring wells G106L and MW-5S. The NAPL was not detected in any other well installed at or adjacent to the site (with the exception of well

MW-105 at which a NAPL was noted during abandonment procedures during Phase II of the RI). Figures 2 and 3 show the elevation of the water table and NAPL over the periods when water levels were collected. Points on the graphs in which ground water elevations are shown without corresponding NAPL elevations represent dates in which no NAPL was observed. Therefore, the NAPL has only been observed when the oil-water interface is below an elevation of 592.5 feet above mean sea level (AMSL) in monitoring wells G106L and MW-5S. Section 4.0 has a description of how high water table conditions would be handled.

In addition, a NAPL was observed when monitoring well G105L was abandoned. As discussed in the RI, this area was not excavated during the soil incineration activities because of the presence of the G105 monitoring well cluster.

2.0 SAMPLING PROGRAM

2.1 Schedule

The schedule is presented in Figure 4. The NAPL field investigation is tentatively scheduled to be conducted at the Lenz Oil site from July 25 to August 18, 1994. Analytical results are expected to be received by September 15, 1994 for the NAPL samples and by August 29, 1994 for the soil samples. All of the data should be validated by October 6, 1994. A technical memorandum will be submitted on October 27, 1994 and a revised feasibility study will be submitted on November 25, 1994. If the NAPL sampling is delayed because of a high water table, a revised schedule for the

submittal of the Technical Memorandum and the revised Feasibility Study (FS) will be necessary and will be proposed to the USEPA and the IEPA.

2.2 Piezometer Locations

As previously indicated, the piezometers will be installed at the approximate locations shown on Figure 1. The actual locations may vary based upon geologic conditions encountered at the site and the presence of nearby utilities. For example, if piezometers are proposed to be in backfill material and the boring logs indicate that they are not, the piezometer location will be moved accordingly. The locations of the piezometers have been selected based on the past presence or absence of NAPL at monitoring wells and soil borings around the site, noted in the respective boring logs of IEPA, which are included in Appendix F of the RI. To show the correlation between the choice of location of the piezometers and the former NAPL sample information, both are plotted on Figure 5.

Six piezometers will be installed around the former location of the G105 well cluster. One of the six (i.e., number P-01) will be located in the unexcavated portion of the well cluster and three in the excavation backfill (i.e., P-02 through P-04) approximately 15 feet away from the former well cluster location. In addition, two piezometers (i.e., numbers P-05 and P-06) will be installed northwest of the well cluster outside of the main excavation to check for the presence of any residual NAPL.

Two additional piezometers (i.e., numbers P-07 and P-08) will be installed on the southwest side of the site and outside of the main excavation to check for the presence of the NAPL north of the G104 well cluster. Although NAPL has not been reported in this area, a sheen was observed in soil boring SB01 and oily material was reported in soil boring SB02 (see Figure 5).

The remaining borings will be situated around the wells G106L and MW-5S. These piezometers are intended to delineate the presence of the NAPL inside the excavation and to the southeast of Jeans Road.

Three of the piezometers (i.e., numbers P-10 through P-12) are located along the southeast edge of the excavation inside the backfill material. If NAPL is present in the excavation, as suggested by its presence in wells G106L and MW-5S, it should be present in these piezometers. Two piezometers (i.e., numbers P-13 and P-14) will be installed between the wells G106L and MW-5S to confirm the continuous extent of the NAPL. The remaining 9 piezometers will complete the delineation of the extent of the NAPL.

Piezom
to NE
SB204
SB206

3.0 PIEZOMETER INSTALLATION AND SOIL SAMPLING

The piezometers will be installed in the unconsolidated materials immediately overlying the bedrock by using the procedures outlined in Section 5.1 of the approved November 1990 Sampling and Analysis Plan (SAP) with the modifications indicated in this section. The piezometers will be developed by using the procedures outlined in Section 5.1 of the SAP a minimum of 48 hours after installation. The piezometers will be constructed out of #304 stainless steel, 10-slot screen and #304 stainless steel risers. The piezometers

will be positioned so that the top of the screen will extend a minimum of 3 feet above the water table. Where possible, 10-foot-long stainless steel screens with 0.01-inch continuous slot openings will be installed. If geological conditions such as shallow bedrock prevent the use of 10-foot-long screens, a screen of appropriate length (5 to 10 feet long) will be used in its place or the screen will be extended into the bedrock. All other well construction procedures will be in accordance with the SAP.

Six piezometers (i.e., P-2, P-3, P-4, P-10, P-11, and P-12) will be installed inside the former excavation area. To prevent perforations in the liner that separates the fill from the native soils, the associated soil borings will be advanced to 1 foot above the bedrock surface as determined from existing soil boring data. Table 1 summarizes the soil boring data available and the maximum depths of the proposed piezometers. If ground water is not encountered within the backfill at the maximum depth of the boring, a piezometer will not be installed and the boring will be backfilled in accordance with the SAP.

At several of the proposed piezometer locations, the underlying soil was not characterized during the RI. As shown on Table 2, the piezometer locations P-1 and P-13 through P-17 are in areas in which samples of the underlying soil from the respective adjacent RI soil borings were not collected to the water table or to the top of the bedrock. At all of the other proposed piezometer locations with an adjacent RI soil boring, soil had been sampled completely to either the water table or the top of bedrock. Piezometers P-18 through P-21 do not have adjacent soil borings.

One soil sample will be collected from the 2-foot interval above the water table at Piezometer locations P-1 and P-13 through P-17 for analysis of the Contract Laboratory Program (CLP) Target Compound List (TCL) volatile organic compounds (VOCs), TCL semivolatile organic compounds (SVOCs), TCL pesticides/polychlorinated biphenyl compounds (PCBs), and Target Analyte List (TAL) metals and cyanide based on the following rationale:

- **P-1** - Samples were not collected from the material adjacent to former wells MW105 in previous investigations.

- **P-13, P-15, and P-16** - Samples were not collected from adjacent soil borings during the RI.

- **P-14 and P-17** - Samples were collected at shallow depths (i.e., to five feet).

If bedrock is encountered prior to reaching the water table at a boring location, a soil sample will not be collected. The soil samples will be collected in a manner similar to the procedures specified in the approved SAP with the exception that 2-inch diameter by 2-foot long split spoons will be used to collect the sample instead of the 5-foot long continuous CME samplers used during the RI activities.

Piezometers P-18 through P-21 will be installed at previously uncharacterized off-site locations. However, soil samples will only be collected from the piezometer locations P-18 through P-21 and analyzed for CLP TCL VOCs, TCL SVOCs, TCL pesticides/PCBs, and TAL metals and cyanide according to the November 1990 SAP if:

- Visual observation in the field indicates that the sample contains NAPL, i.e., because it is stained or has an oily appearance; and/or

- Field screening with a photoionization detector (such as an HNu detector) indicates that concentrations of volatile organics in the sample are elevated with respect to other soil sample locations.

If field observations and screening indicate NAPL is likely present, a soil sample will be collected from the 2-foot interval above the water table.

Soil samples will not be collected from the piezometer locations P-2 through P-12 and P-22 based on the following rationale:

- **P-2 through P-4** - Soil samples were collected to the base of the excavation from the adjacent soil boring (SB07) during the RI, thereby adequately characterizing the soil constituents.

- **P-5** - Soil samples were collected to a depth of 12.9 feet at the adjacent soil boring (SB20) during the RI.

- **P-11** - Soil samples were collected to the base of the excavation at the adjacent soil boring (SB11) during the RI.

- **P-6 through P-10, P-12, and P-22** - Soil samples were collected to bedrock from adjacent soil borings during the RI, thereby adequately characterizing the soil constituents.

If NAPL is encountered during the drilling of piezometers P-2 through P-12 and P-22 (i.e., based on visual observation and field screening), the NAPL sampling results and the geotechnical results from the RI will be used to estimate the concentration of each NAPL constituent in the soil. The concentration of each parameter in the soil will be calculated by: (1) using the residual NAPL saturation (as defined on page 5-17 of the ARMOS© user's guide contained in Enclosure 1 to Attachment 3 of this FSP Addendum A) and the specific gravities of the NAPL and the soil to determine the weight of NAPL per weight of soil, and (2) multiplying this number by the concentration of each individual chemical parameter detected in the NAPL. In addition, a maximum of three NAPL-contaminated soil samples will be collected and analyzed for CLP TCL VOCs, TCL SVOCs, pesticides/PCBs, and TAL metals and cyanide to confirm these calculated concentrations.

Soil samples will be collected in a manner similar to the procedures specified in the approved SAP with the exception that 2-inch diameter by 2-foot long split spoons will be used to collect the sample instead of the 5-foot long continuous CME samplers used during the RI activities. For quality assurance/quality control (QA/QC) purposes, one rinsate blank of the decontaminated split spoon will be collected. In addition, a duplicate sample and a matrix spike/matrix spike duplicate (MS/MSD) sample will also be collected. The sample handling and packaging procedures outlined in the SAP and the QA/QC procedures included in the January 1992 Quality Assurance Project Plan (QAPP) Addendum will be followed. Environmental Standards, Inc. of Valley Forge, Pennsylvania will validate the soil data.

4.0 NAPL SAMPLING AND ANALYSIS

Prior to sampling, the water levels in monitoring wells G106L and MW-5S will be measured to determine the elevation of the ground water-NAPL interface. If the elevation of this interface exceeds 592.5 feet AMSL, the NAPL sampling will be postponed. As previously discussed, the NAPL is not generally present in the existing monitoring wells when the water table exceeds this elevation. To confirm the presence or absence of the NAPL in any of the new piezometers, the water table must be below the specified elevation. The USEPA will be immediately notified if a high water table is found, and the site water levels will be measured on a weekly basis until the water table is low enough for proper NAPL sampling. The schedule of the submittals to the USEPA and IEPA will be modified to incorporate the delays, as discussed in Section 2.0.

Based upon the results of the NAPL sampling, and in consultation with the USEPA and IEPA, additional piezometers may be installed if NAPL is detected in any of the outer ring piezometers (i.e., piezometers P-05 through P-09, P-12, P-17, P-18, and P-20 through P-22). Additional piezometers will be installed as needed to determine the extent of the NAPL.

4.1 Thickness Measurement

Prior to well development, one week after well development, and two weeks after well development, the NAPL thickness will be measured in all of the piezometers and shallow monitoring wells as described below. The actual date of sampling will be dependent upon the volume of NAPL in the well.

A Keck Instruments, Inc. (Keck) KIR-89 Interface Probe will be used to measure the depths to the NAPL and water. The instrument does not require calibration in the field. A standard operating procedure (SOP) for the measurement of depths to the NAPL and ground water, and an instruction manual (including maintenance practices) for the Keck KIR-89 probe are included in Attachments 1 and 2, respectively. The specific gravity of the NAPL samples collected as part of the RI ranged from 0.87 to 0.88. This is well above the Keck KIR-89 probe's lower detection limit of 0.75.

Field method calc. NAPL thickness req. AP

The NAPL and water levels will be determined to the nearest 0.01 of a foot with an accuracy of $\pm$ 0.02 feet. The thickness of the NAPL will be calculated from the measurements of the depths to the NAPL and water by using the procedure described in the instrument's manual. Because this procedure requires the determination of the specific gravity of the NAPL, a sample for specific gravity analysis will be collected at

each location where sufficient volume of NAPL is present (see Table 3 for the minimum required sample volumes).

An evaluation of the true NAPL thickness will be made by performing an empirical estimate and a bail down test in all piezometers in which the NAPL thickness exceeds 0.10 feet. Bail down tests and empirical methods are necessary because the thickness of NAPL measured inside a well or piezometer is typically greater than the actual thickness of the NAPL on the water table as a result of the capillary action of the soil particles. As NAPL collects in a piezometer, the water level in the well is depressed and an equilibrium is reached between the product and ground water. The difference between the actual thickness and the apparent thickness of the NAPL is typically greater in deposits of fine soils such as clay, silt, and fine-grained sand and less in deposits of coarse-grained sands and gravel. A detailed discussion of apparent product thickness, actual product thickness, and grain size is included in "Volume Determination and Recoverability of Free Hydrocarbon" by Testa and Paczkowski (Ground Water Monitoring Review, Winter 1989, page 120).

Bail Down Test

The bail down tests will be performed by using the following procedures:

- Prior to the bail down test, the depth to NAPL and depth to water will be measured by using an interface probe as described in Attachment 1;

- The piezometer will be rapidly purged of all NAPL by using a disposable bailer;

- The depth to NAPL and depth to water will be determined at 2-minute intervals for the first ten minutes followed by 5-minute intervals thereafter by using the interface probe; and

- The measurements will be collected until the depth-to-water change is less than 0.02 feet (i.e., the accuracy of the interface probe) for three consecutive readings, or the levels have reached 90 percent of the original measurement. A minimum of 10 minutes of measurements for each test will be collected.

The depth-to-water values from each bail down test will be plotted versus time. The true formation NAPL thickness will be determined from the thickness of the NAPL at the time when the depth-to-water curve passes through the inflection point (i.e., when the depth-to-water curve changes from an increasing curve to a decreasing curve). A detailed summary of this procedure, the theory behind the procedure, and analysis of the data are included in the aforementioned publication.

Empirical Method

The empirical method of estimating the true NAPL thickness and volume will entail the application of Environmental Systems & Technologies, Inc.'s computer program Areal Multiphase Organic Simulator ARMOS©. A copy of the ARMOS© users' guide which

details the methods used in the program, the site specific input parameters, and the assumptions to be made when using ARMOS© are located in Attachment 3. ARMOS© can calculate and graphically display: (1) a contour map of oil for the area, (2) estimation error contours, and (3) profiles of the water and the total liquid saturation for specific locations.

4.2 NAPL Sampling and Analysis

The physical and chemical properties of the NAPL will be reevaluated to confirm the RI results. The samples of the NAPL will be collected from piezometers selected as indicated in Section 1.0, and submitted for laboratory analysis. The piezometers to be sampled will be selected in consultation with the USEPA and IEPA based upon NAPL thickness and distribution. Depending upon the NAPL found at the site, it is estimated that up to five samples will be analyzed. The NAPL samples will be analyzed as medium concentration samples for: (1) TCL VOCs, SVOCs, and pesticides/PCBs; (2) TAL total metals and cyanide; (3) Toxicity Characteristic Leaching Procedure (TCLP) organics and inorganics; (4) specific gravity; (5) kinematic viscosity; and (6) gas chromatography fingerprinting. If a sufficient volume of sample is not present in the piezometer to collect all of the required volume, the analyses will be performed in the following order: specific gravity, kinematic viscosity, TCL SVOCs, TCL VOCs, TCL pesticides/PCBs, TCLP inorganics, TCLP organics, TAL metals and cyanide, and gas chromatography fingerprinting. MS/MSD analyses will be provided only if sufficient sample volume is available to run all of the analyses. The sample volume, containers, and preservation requirements are shown in Table 3. All of the samples will be submitted to RMAL Laboratory (RMAL), located in Arvada, Colorado. Based on the results of these sample analyses and the data regarding distribution of the NAPL, it may

prioritize

be necessary to collect samples from additional NAPL locations and analyze for a modified list of parameters.

With the exception of gas chromatography fingerprinting, the analyses will be performed in accordance with the procedures specified in the QAPP Addendum, dated January 1992. The gas chromatography fingerprinting procedures are not specified in the QAPP. However, because the results of the gas chromatography fingerprinting will be used only as an attempt to determine if different types of NAPL are present at the site, the analytical method does not require as strict a set of QA/QC procedures as the rest of the analyses, and no revision of the QAPP is considered necessary.

The NAPL sample will be collected as follows:

- The interface probe, bailer, rope, and any other equipment to be inserted in the well will be decontaminated in accordance with the procedures presented in Section 5.2 of the SAP.

- The depth to water and the depth to the NAPL will be measured by using the interface probe.

- A clear, bottom-filling, Teflon bailer will be dedicated to the well and used to withdraw the NAPL sample.

- The sample will then be dispensed from the bailer into jars supplied by RMAL as indicated in Table 3.

- The NAPL samples do not require preservation, but will be cooled to 4°C for shipment to RMAL.

- The samples will be shipped to the laboratory under strict chain-of-custody procedures as described in Section 5.0 of the approved January 22, 1992 QAPP Addendum. Because the NAPL samples are considered medium-concentration samples, they will be shipped to the laboratory in accordance with Department of Transportation Regulations for potentially hazardous materials.

Field investigations have shown that an insufficient quantity of the NAPL is present to collect both an investigative and a duplicate sample from each piezometer. Therefore, unless other conditions are discovered, a duplicate sample will not be collected. Because a comparison of the low-concentration trip and field blank results to the medium-concentration NAPL results would be meaningless, no field or trip blank samples will be collected. In fact, the detection limits for medium-concentration samples are higher than the concentrations of contaminants generally detected in trip and field blank samples.

Split sample

The NAPL investigation and analyses will be performed in accordance with the methods described in the January 1992 QAPP Addendum. The samples will be shipped via overnight courier to RMAL. Notice will be given to the USEPA and the IEPA at least 10 days prior to sampling the NAPL, and the agencies will be permitted to split samples if a sufficient volume of NAPL is present in the well. As indicated in the January 1992

QAPP Addendum, Environmental Standards, Inc. of Valley Forge, Pennsylvania will validate the NAPL data.

4.3 Sample Designation

The sample designation for the NAPL samples will be as follows:

- Characters 1 and 2 - LO to indicate Lenz Oil;
- Character 3 - an N to indicate NAPL sampling; and
- Characters 4, 5, and 6 - the piezometer number.

For example, the designation LONP01 will designate the NAPL sample from piezometer P-01 at Lenz Oil.

The sample designation for the soil samples will be as follows:

- Characters 1 and 2 - LO to indicate Lenz Oil;
- Character 3 - an S to indicate soil sampling; and
- Characters 4, 5, and 6 - the piezometer number.

For example, the designation LOSP17 will designate the soil sample collected from piezometer P-17 at Lenz Oil.

4.4 Recoverable NAPL Determination

The total recoverable volume of the NAPL is dependent on the site physical properties, the NAPL characteristics, and the remedial technology implemented at the site. The numerical model ARMOS© will be used to project the maximum volume of recoverable NAPL based upon data collected during this and previous investigations. ARMOS© is capable of simulating the recovery of hydrocarbons from trenches or recovery wells in order to facilitate the design of remediation schemes. The ARMOS© users' guide containing a detailed theoretical discussion of the model and the assumptions to be made when using ARMOS© are included in Attachment 3. A complete discussion of modeling results will be included in the revised FS.

5.0 DATA REPORTING

Data collected during the NAPL investigation will be included in a Technical Memorandum to be submitted to the USEPA and the IEPA. These data will be used in Revision 1 of the FS to evaluate both the alternatives already proposed and any new alternatives that may become, based upon the data results, potentially viable remedial alternatives for the Lenz Oil site.

TABLES

TABLE 1

MAXIMUM BORING DEPTHS FOR PIEZOMETERS LOCATED INSIDE THE EXCAVATION[1] LENZ OIL SITE LEMONT, ILLINOIS

Piezometer	Adjacent Boring	Depth to Water	Depth to Liner	Depth to Bedrock	Depth of Adjacent Boring	Maximum Depth of Proposed Piezometer
P-2	SB-07	NE	<8	8	9	7
P-3	SB-07	NE	<8	8	9	7
P-4	SB-07	NE	<8	8	9	7
P-10	SB-12(II)	NE	NP	5	8.1	4
P-11	SB-11(II)	NE	NE	NE	7.5	7.5
P-12	SB-22	NE	NP	NE	9.5	9.5

Note:

[1] All depths are in feet.

Key:

NE = Not encountered.
NP = Liner not present in soil samples collected.

TABLE 2

SUMMARY OF INFORMATION COLLECTED FROM SOIL BORINGS NEAR THE PROPOSED PIEZOMETERS (1) LENZ OIL SITE LEMONT, ILLINOIS

Piezometer	Depth to Water BGS (2)	Nearby Soil Borings					
		Location (3)	Adjacent Soil Boring	Total Depth BGS	Depth to Water BGS	Depth to Bedrock BGS	Soil Interval Sampled
P-1	6.5	Inside	SB07(I)	9	NE	8	2.5-5, 5-9
P-2	6.5	Inside	SB07(I)	9	NE	8	2.5-5, 5-9
P-3	6.5	Inside	SB07(I)	9	NE	8	2.5-5, 5-9
P-4	6.5	Inside	SB07(I)	9	NE	8	2.5-5, 5-9
P-5	6.5	Outside	SB20(I)	12.9	NE	NE	2.5-4.5,4.5-9.5,9.5-12.9
P-6	6.5	Outside	SB06(I)/SB19(II)	8.7/11.5	NE/8.0	8.7/11.5	2.5-5,5-8.7/0-5,5-10,10-11.5
P-7	6.5	Outside	SB01(I)	12.5	7.5	12.5	0-5,5-9,9.5-12.5
P-8	7	Outside	SB02(I)	8.7	NE	8.7	0-4.5,4.5-7.5,7.5-8.7
P-9	8	Outside	SB14(II)/SB21(I)	12.1/14.5	4.0/9.5	12.1/14.5	5-10,10-12.1/0-2.5,9.5-14.5
P-10	8	Inside	SB12(II)	8.1	NE	8.1	0-5, 5-8.1
P-11	8	Inside	SB11(II)	7.5	NE	NE	0-5, 5-7.5
P-12	7.5	Inside	SB22(II)	15	NE	12.8	0-5,5-10,10-15
P-13	8.5	Outside	MW05	54.5	9.2	26.5	none collected
P-14	9	Outside	SB211(II)	5	NE	NE	0-3,3-5
P-15	9	Outside	G106DR	45	9.5	13	none collected
P-16	10	Outside	MW05	54.5	9.2	26.5	none collected
P-17	10	Outside	SB16(I)	4.5	NE	4.5	0-4.5
P-18	N/A	Off site	N/A	N/A	N/A	N/A	N/A
P-19	N/A	Off site	N/A	N/A	N/A	N/A	N/A
P-20	N/A	Off site	N/A	N/A	N/A	N/A	N/A
P-21	N/A	Off site	N/A	N/A	N/A	N/A	N/A
P-22	N/A	Outside	SB12(II)/SB16(I)	8.1/4.5	NE	8.1/4.5	0-5,5-8.1/0-4.5

Notes:

(1) All units are in feet.
(2) Based on the average of the four water levels presented in the Remedial Investigation Report.
(3) Inside/outside refers to the excavation, and off site refers to the site.

Key:

BGS = Below ground surface
NE = Not encountered.
N/A = Not applicable.

TABLE 3

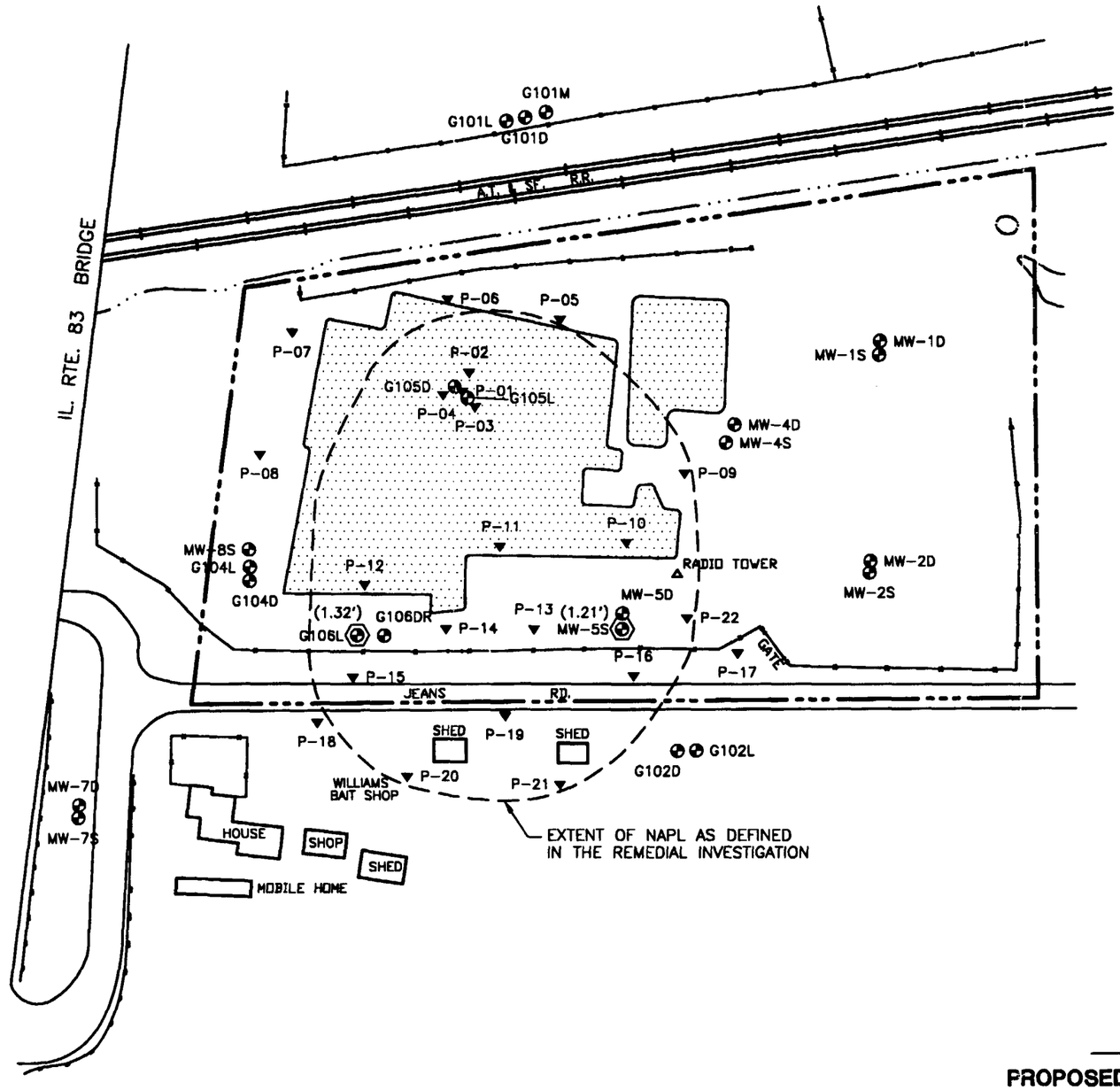
SAMPLE VOLUME, CONTAINERS, AND PRESERVATION TECHNIQUES FOR NAPL SAMPLES[1]
LENZ OIL SITE
LEMONT, ILLINOIS

Matrix	Analytical Fraction	Container	Preservation	Filling Procedures	Maximum Holding Times
NAPL	TCL Volatile Organic Compounds	3 - 40 ml VOC vials	None	Zero headspace - no air bubbles	14 days
NAPL	TCL Semivolatile Organic Compounds, PCBs/Pesticides	1 - 8 oz. wide-mouth glass bottle	None	Not Applicable	7 days from collection or 5 days from VTSR, 40 additional days for analysis
NAPL	TAL Total Metals/Cyanide	To be taken from the semivolatiles bottle	None	Fill to neck of bottle	6 months except for Hg which is 26 days
NAPL	Viscosity/Specific Gravity	100 gram sample to be taken from the 32-oz. TCL SVOC bottle or the VOC vials if insufficient volume is collected	None	Not Applicable	Not Applicable
NAPL	TCLP	1 - 32 oz. wide-mouth glass bottle 1 - 4 oz. wide-mouth glass bottle	None	Zero headspace - no air bubbles for VOC vial	Per SW846-131 protocol
NAPL	GC/FID Fingerprint	1 - 4 oz. wide-mouth glass bottle	None	Fill to neck	Not Applicable

Note:
[1] Adapted from January 1992 Quality Assurance Project Plan Addendum.

Key:
NAPL = Nonaqueous phase liquid
TCL = Target compounds list
VOC = Volatile organic compounds
TAL = Target analyte list
SVOC = Semivolatile organic compounds
TCLP = Toxicity Characteristic Leaching Procedure
GC/FID = Gas chromatography/flame ionization detector

FIGURES



APPROX. SCALE (ft.)

0 100

SYMBOL LEGEND

- AREA OF EXCAVATION
- DRAINAGE DITCH
- PROPERTY LINE
- FENCE LINE
- RAILROAD
- PROPOSED PIEZOMETER LOCATION
- MONITORING WELL LOCATION
- MONITORING WELLS WHERE NAPL WAS OBSERVED
- (1.21') MAXIMUM APPARENT PRODUCT THICKNESS (FEET).

NOTE:

1. LOCATIONS ARE BASED ON IEPA FIELD MEASUREMENTS AND HAVE NOT BEEN SURVEYED. THERFORE, LOCATIONS SHOULD BE CONSIDERED APPROXIMATE.
2. NAPL WAS OBSERVED IN WELL G105L DURING ABANDONMENT.

FIGURE 1

PROPOSED PIEZOMETER LOCATIONS
LENZ OIL SITE
LEMONT, ILLINOIS

ERM

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FK
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Figure 2

Elevation of Water Table and NAPL

G106L Well

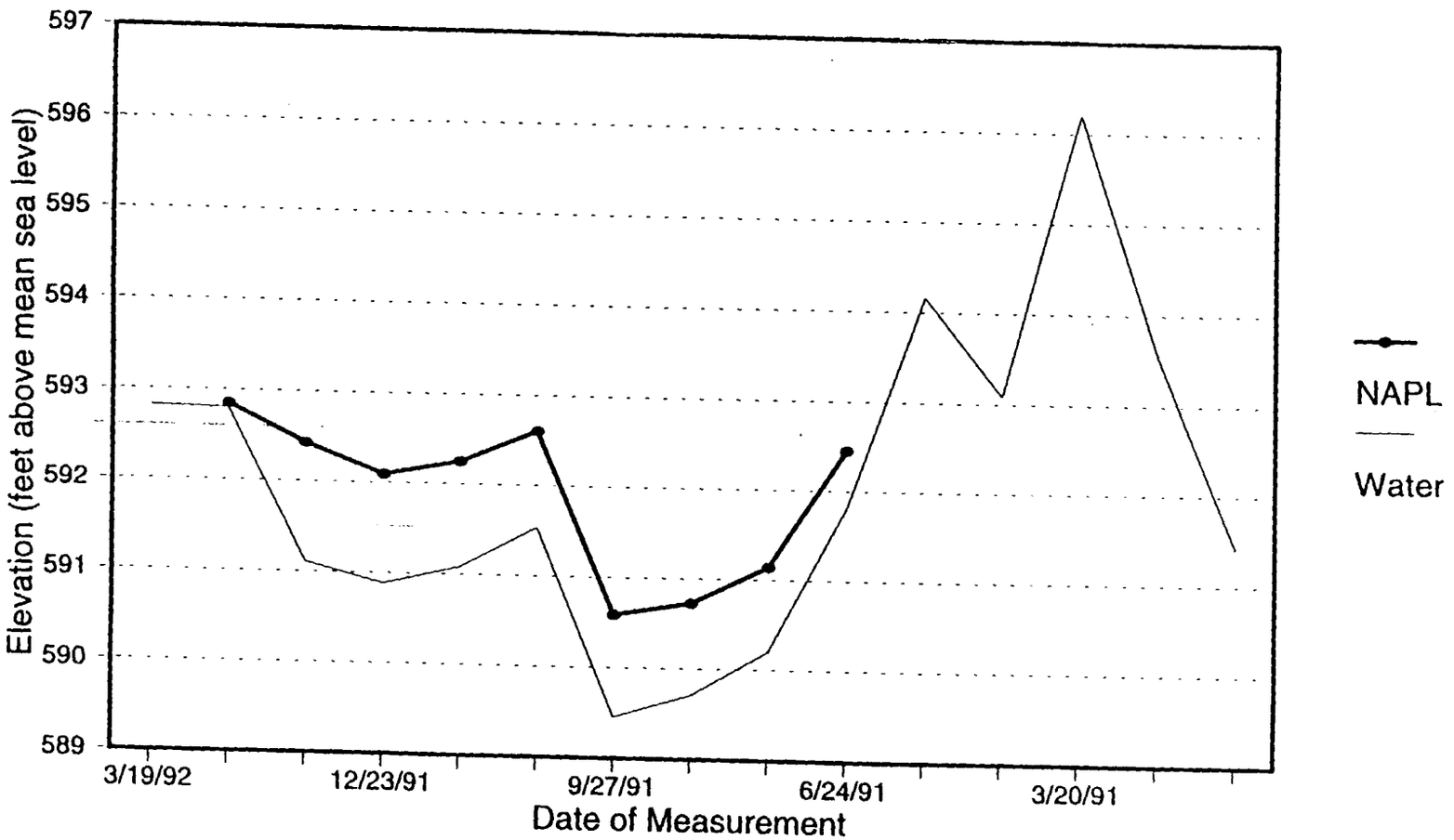


Figure 3

Elevation of Water Table and NAPL

MW-5S Well

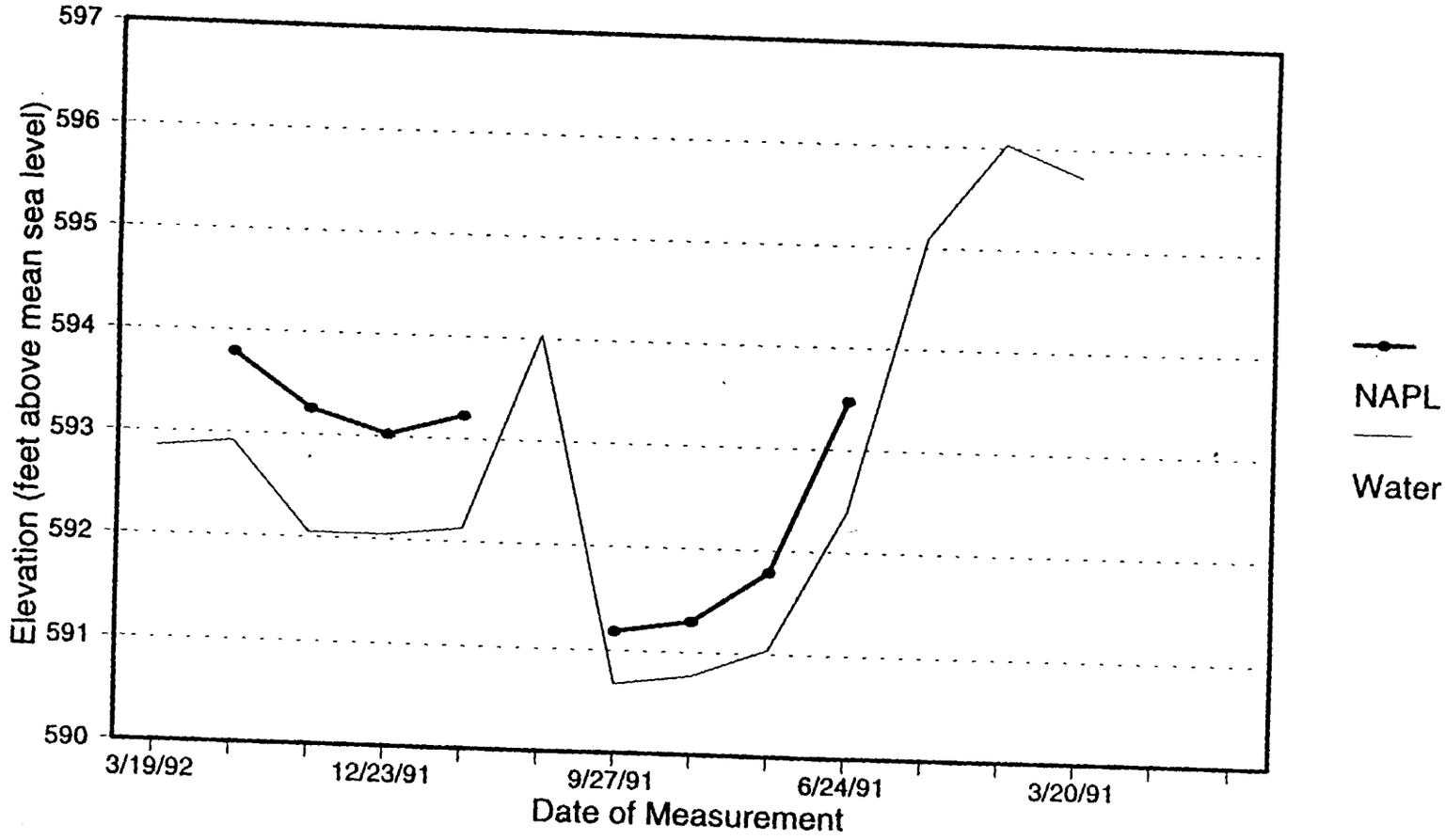


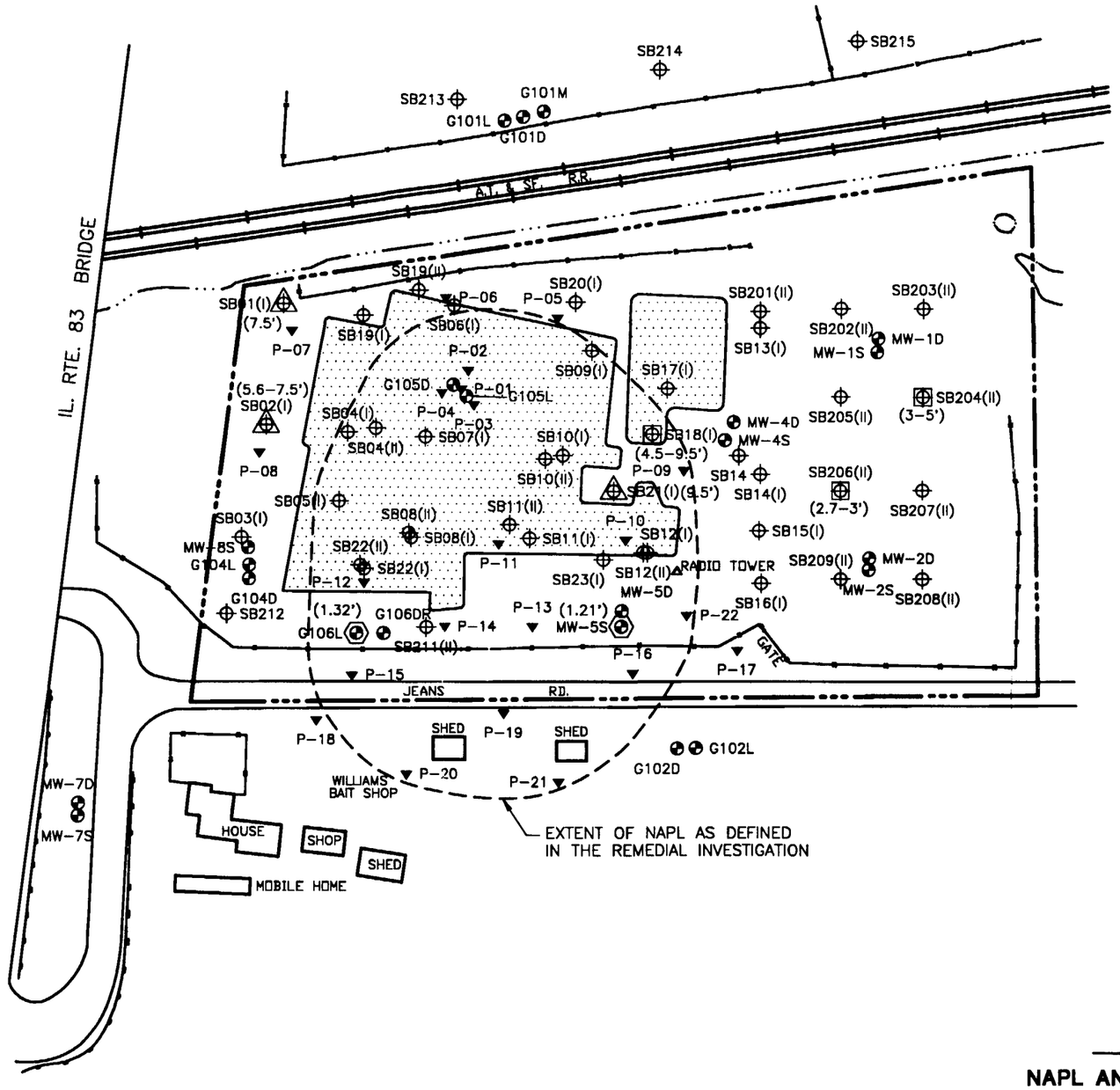
FIGURE 4
TENTATIVE SCHEDULE FOR COMPLETION OF REVISION 1 OF THE FEASIBILITY STUDY

ID	Task Name	7/17	7/24	7/31	8/7	8/14	8/21	8/28	9/4	9/11	9/18	9/25	10/2	10/9	10/16	10/23	10/30	11/6	11/13	11/20
			August						September				October				November			
1	**FIELD INVESTIGATION**																			
2	Install and Develop Piezometers																			
3	Measure NAPL Thickness																			
4	Measure NAPL Thickness and Perform Baildown T																			
5	Measure NAPL Thickness and Sample Piezometers																			
6	**TECHNICAL MEMORANDUM**																			
7	RMAL Analyses Samples																			
8	Validate Data																			
9	Prepare Technical Memorandum																			
10	Submit Technical Memorandum																			
11	**REVISE FEASIBILITY STUDY**																			
12	Incorporate NAPL Data Into FS																			
13	Submit Revision 1 of the FS																			

10a - Agency review of Tech Memo
30 days to 11/7 ?

Project: FIGURE 4
Date: 6/6/94

Task — Milestone — Rolled Up Task — Rolled Up Progress
Progress — Summary — Rolled Up Milestone



APPROX. SCALE (ft.)

0 100

SYMBOL LEGEND

- AREA OF EXCAVATION
- DRAINAGE DITCH
- PROPERTY LINE
- FENCE LINE
- RAILROAD
- SOIL BORING LOCATION
- PROPOSED PIEZOMETER LOCATION
- MONITORING WELL LOCATION
- MONITORING WELLS WHERE NAPL WAS OBSERVED
- (1.21') MAXIMUM APPARENT PRODUCT THICKNESS OF NAPL (FEET).
- OIL STAIN OBSERVED IN SOIL
- (3-5') DEPTH AT WHICH OIL STAIN WAS OBSERVED (FEET).
- SHEEN OBSERVED IN SOIL/WATER
- (7.5') DEPTH AT WHICH SHEEN WAS OBSERVED (FEET).

DWG 5/23/94 FK PLD K:\CPFILES\ERM\SBA\94017\ACAD\FSP\FIG4.DWG MAY 23, 1994 12:56 PM

NOTE:

1. LOCATIONS ARE BASED ON IEPA FIELD MEASUREMENTS AND HAVE NOT BEEN SURVEYED. THERFORE, LOCATIONS SHOULD BE CONSIDERED APPROXIMATE.
2. NAPL WAS OBSERVED IN WELL G105L DURING ABANDONMENT.

FIGURE 5

NAPL AND OIL STAIN LOCATIONS
LENZ OIL SITE
LEMONT, ILLINOIS

ERM

ATTACHMENT 1

FIELD MEASUREMENT OF DEPTH TO GROUND WATER AND NONAQUEOUS PHASE LIQUID

ATTACHMENT 1
FIELD MEASUREMENT OF DEPTH TO GROUND WATER AND NONAQUEOUS PHASE LIQUID

Method: Ground water and light nonaqueous phase level readings by using an electric interface probe.

Range of measurement: 0 to 100 feet
Sensitivity: 0.01 foot
Accuracy: 0.02 foot
Sample matrix: In situ ground water and nonconductive liquid

Equipment and supplies:

1. Electric interface probe (Keck Instruments, Inc. KIR-89 or equivalent)
2. Alconox or similar trisodium phosphate (TSP) detergent
3. Potable water
4. Distilled water
5. Laboratory-grade hexane
6. Plastic bucket and brushes
7. Paper towels
8. Spray bottles

Procedures:

The interface probe will be operated in accordance with the manufacturer's instructions attached to this standard operating procedure (SOP). If equipment other than the type listed in this SOP is used, the manufacturer's manual for the specific device will be consulted.

A. Decontamination

The interface probe will be decontaminated before the collection of every round of water level readings according to the following method:

1. The meter tip and measuring tape will be washed with a solution of potable water and Alconox (or similar TSP detergent) in a plastic bucket with a plastic scrubbing brush. The water tip and measuring tape will then be wiped with a paper towel soaked in laboratory-grade hexane. Distilled water will be poured over the tip and tape as a final rinse.

2. The body of the meter will be wiped clean with paper towels, dampened with a solution of potable water and Alconox (or similar TSP detergent), and then wiped with paper towels dampened with distilled water.

3. The tip, tape, and body of the water level meter will be allowed to air dry.

The interface probe will be decontaminated between each piezometer during each round of level measurements by the following method:

1. The meter tip and the portion of the measuring tape that come into contact with ground water or the interior of the piezometer will be washed with a solution of potable water and Alconox (or similar TSP detergent).

2. The meter tip and measuring tape will then be wiped with a paper towel soaked in laboratory-grade hexane.

3. Distilled water will be sprayed on the tip and tape of the meter as a final rinse.

B. Equipment operation check

1. Before the water and nonaqueous phase level readings are taken at a piezometer, the meter buzzer and light will be checked by using the test button. If the buzzer does not sound or the indicator light is not lit, the batteries will be replaced. If this does not correct the problem, the meter will be returned to the manufacturer for repair.

2. No additional calibration is required.

C. Field measurements

1. The level measurements will be taken by slowly lowering the meter tip and tape into the piezometer until the buzzer and the light signal that a nonaqueous phase liquid or water has been reached. A continuous light and audible sound will indicate contact with a nonaqueous phase layer. An oscillating light and audible sound will indicate contact with water. The measuring point on the piezometer will be the north side of the piezometer or a point previously marked by a surveyor.

2. The meter tip and tape will be raised and lowered until the buzzer and light signal are repeated twice at a given point.

3. The value will be recorded in the fieldbook.

4. If the first reading is a nonaqueous phase layer, the probe will be lowered farther until the audible signal and light begin to oscillate and thereby indicate the presence of water. This reading will also be recorded in the field notebook.

Equipment care:

1. The battery must be replaced after extended use. The replacement procedure and type of battery used will conform to the manufacturer's guidelines.

2. When not in use, the meter will be kept in a protected location away from temperature extremes and precipitation, such as in a vehicle or other protected area.

3. Excessive use may weaken the wires inside the measuring tape. Care will be taken not to bend or kink these wires and to limit the stress to which they are exposed.

ATTACHMENT 2

INSTRUCTION MANUAL FOR THE KIR-89 INTERFACE PROBE

INSTRUCTION MANUAL

KIR-89

INTERFACE PROBE & REEL

KECK INSTRUMENTS, INC.
An Environmental Science & Engineering Company
1099 West Grand River Avenue = Williamston, Michigan 48895
= Phone (800) 542-5681

INSTRUCTION MANUAL

KIR-89

Interface Probe
and Reel

TABLE OF CONTENTS

Page

KECK

INSTRUMENTS, INC.

1 INTRODUCTION

KIR-89
INTERFACE PROBE & REEL

The Keck Instruments, Inc. KIR-89 Interface Probe is a portable reel-mounted instrument capable of providing accurate product level and thickness with water level measurements. The KIR-89 features a Tefzel coated engineer's tape marked in feet and 100ths of a foot permanently affixed to a polypropylene downhole probe. The probe uses a phenolic float to detect product level and a pair of stainless steel contacts for conductive fluids (water). The presence of product and water is indicated by the following devices:

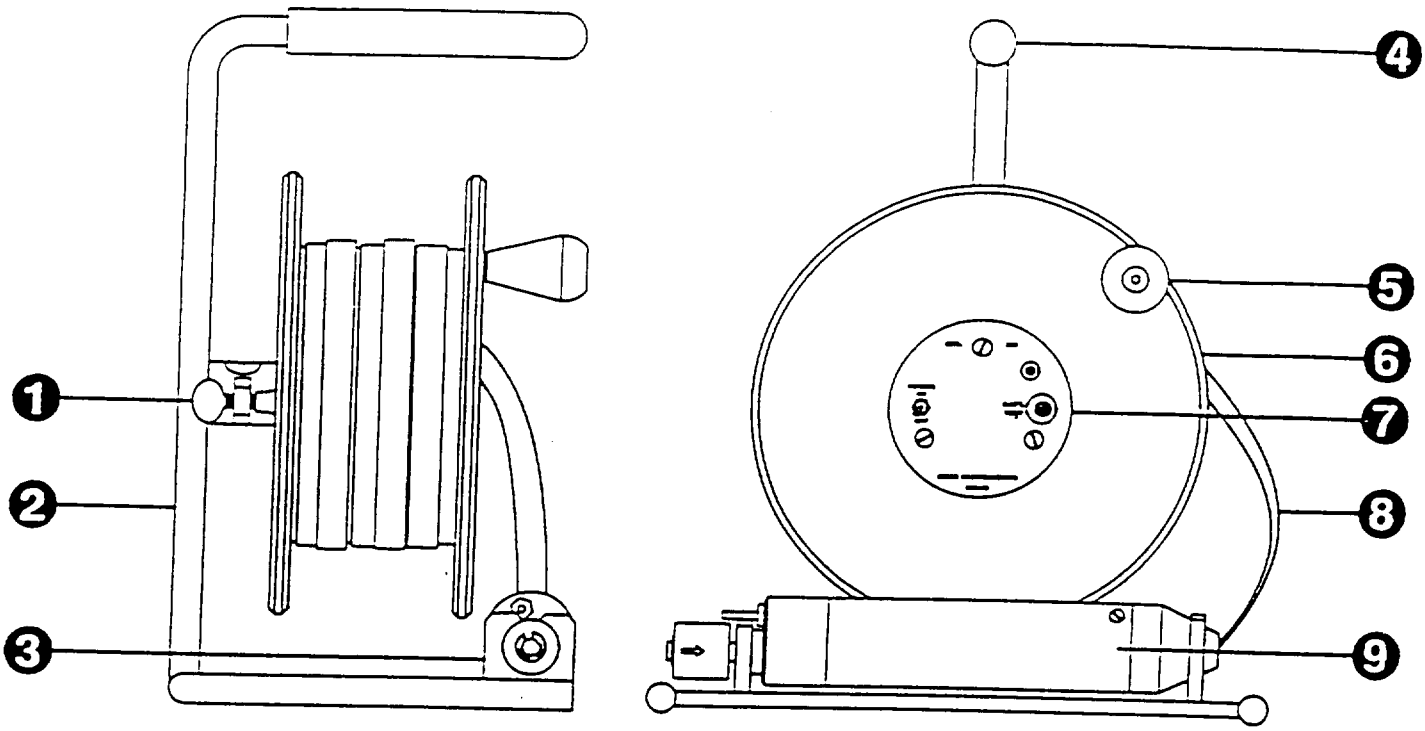
1. Visual indicator (red light)
2. Audible indicator (buzzer)

The instrument is powered by a replaceable 9 volt DC battery mounted behind the KIR faceplate.

THEORY OF OPERATION

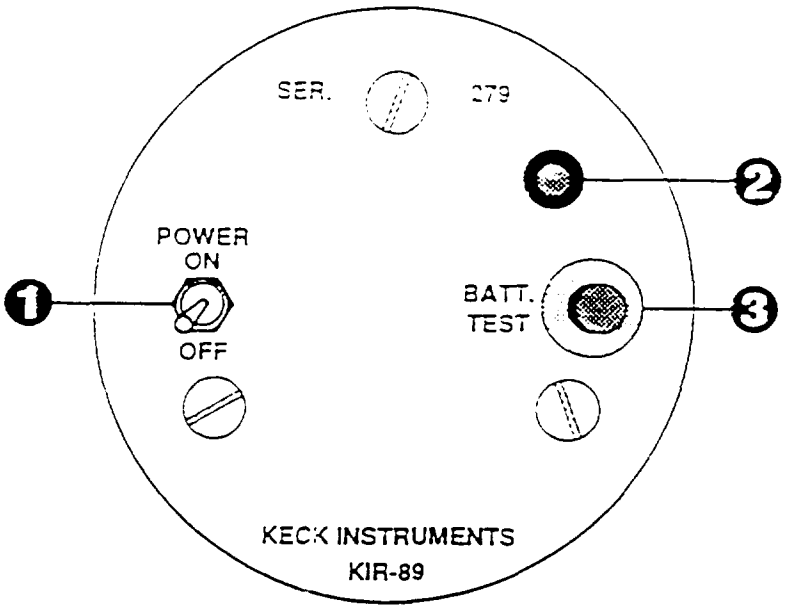
When the KIR-89 Probe is lowered down the well, the float switch will activate the light and audible signal at the first fluid level. The float will detect any fluid with a specific gravity of .75 or greater. As the probe is lowered deeper into the well the stainless steel contacts touch water (a conductive fluid), the steady light and the audible signals will begin to oscillate. If the first fluid is not water, and therefore non-conductive, the emitted light and audible signals will be continuous.

2 INTERFACE PROBE & REEL



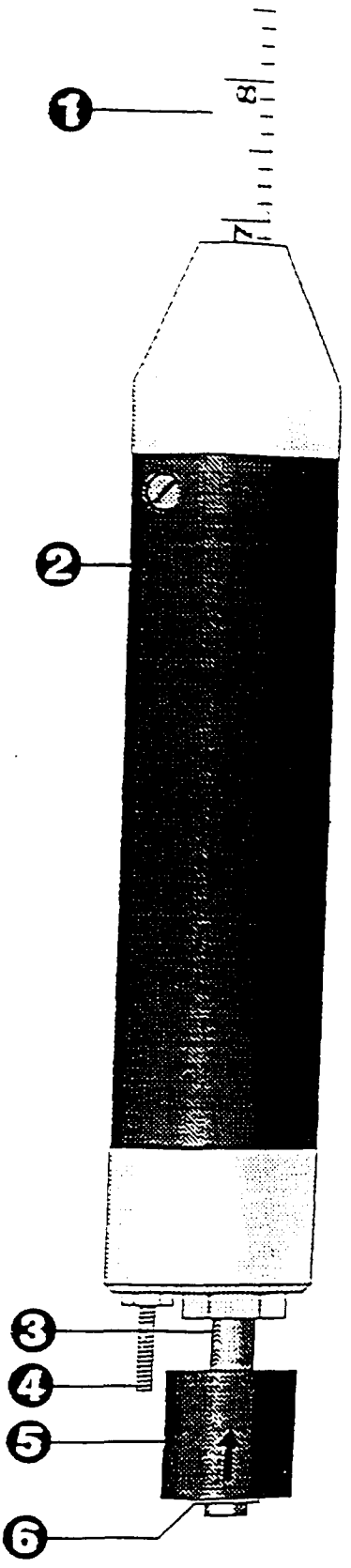
1. Brake
2. Frame
3. Retaining Clip
4. Carry Handle
5. Reel Handle
6. Storage Reel
7. Face Plate
8. Engineer's Tape
9. Downhole Probe

FACEPLATE



1. Power On/Off Switch
2. Light Signal
3. Battery Test Button

KIR-89 PROBE



1. Engineer's Tape
2. Polypropylene Probe
3. Float Shaft
4. Adjustable Contact
5. Phenolic Float
6. "E" Clip

3 OPERATION PROCEDURE

Testing Battery, Signals

Step 1

Turn the instrument power switch to on and press the battery test button. A loud audible signal and bright light indicates adequate battery voltage for proper operation.

Step 2

Remove the probe from the retaining clip and engage the phenolic float. A continuous audible signal and light should be present. With the float engaged, moisten finger tips and make contact with the float shaft and the adjustable contact. The steady tone and light should begin to oscillate thus indicating proper operation of the device.

Measuring Fluid Levels

Step 1

Lower the KIR-89 probe down the well until a continuous audible signal and light is indicated. Take the footage measurement from the tape at the top of casing or other reference point and record this figure as the first fluid level.

Step 2

Continue to lower the probe until the audible signal and light begin to oscillate. Record the footage measurement from the reference point as the second fluid level.

⚠ IMPORTANT

To maintain an accuracy of plus or minus 0.01 ft., the specific gravity of the product to be measured must be accounted for. To calculate the required correction factor, identify the specific gravity of the product, then refer to the "Measurement Correction" chart on page 7. The correction factor will be used in the following equations.

Calculating Product Thickness

Subtract the first fluid level from the second fluid level, then add the specific gravity correction factor taken from the chart on page 7. This is the thickness of the product layer.

Example:

Specific gravity of product = 0.8
1st fluid level = 10.0'
2nd fluid level = 12.5'
Correction factor from chart = -0.015'
12.5' - 10.0' + (-0.015') = 2.485' product thickness

Calculating Product Level

Add the specific gravity correction factor taken from the chart on page 7 from the first fluid level. This is the product level.

Example

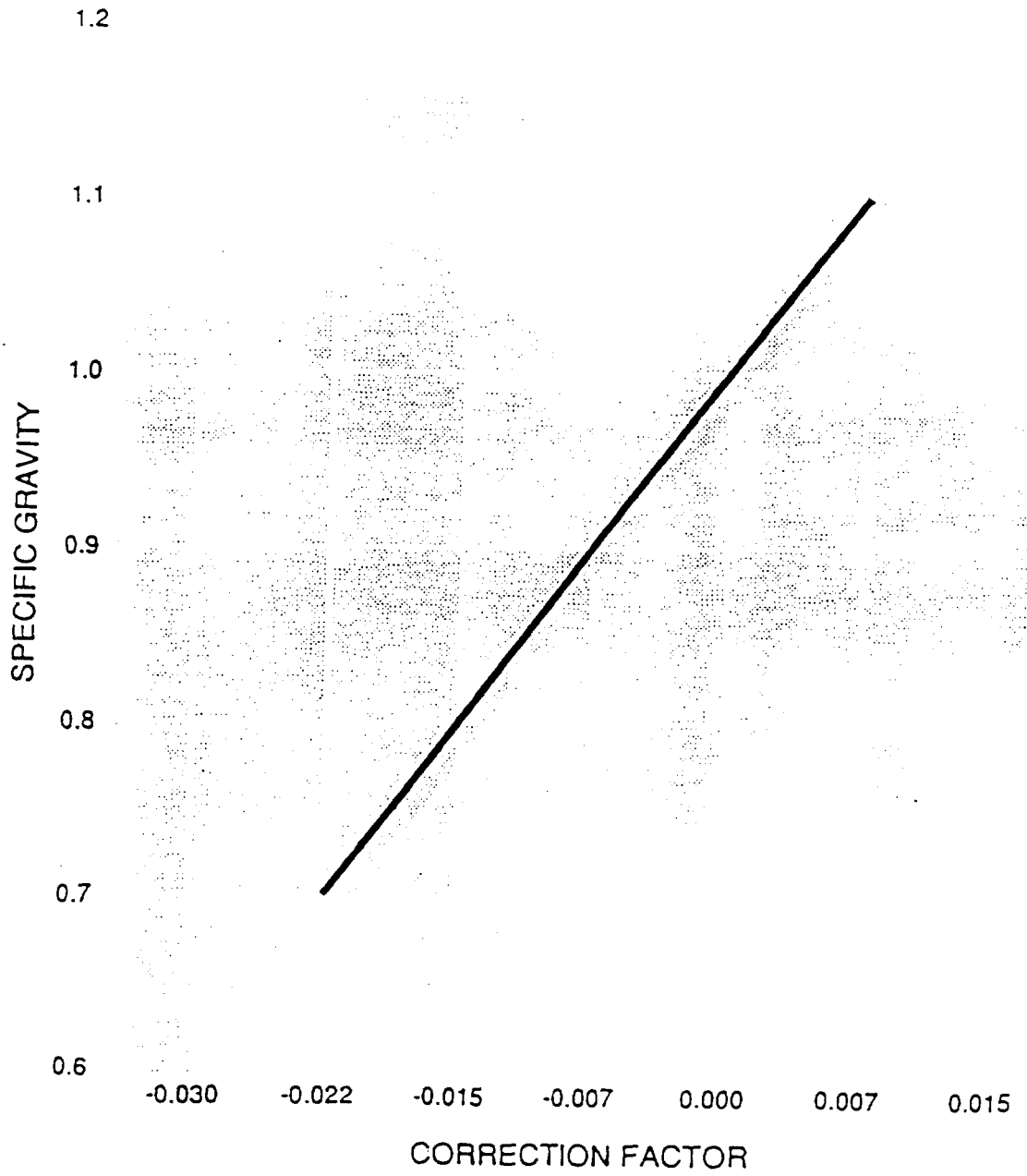
Specific gravity of product = 0.9
first fluid level = 15.25'
Correction factor from chart = -0.007'
15.25' + (-0.007') = 15.242' product level

Measuring Water Levels in Product Free Wells

The lack of a continuous tone and light with an oscillating audible signal and light will indicate absence of any nonconductive fluid on the surface of the water.

QUESTIONS? Call 1-800-542-5681

KIR-89
MEASUREMENT CORRECTION CHART



Factor = 0.075 (specific gravity) - 0.075

4 DECONTAMINATION & CLEANING

Cleaning Procedure

The KIR-89 can be cleaned with any detergent such as Trisodium Phosphate (TSP), Alkenox or Liquenox. If other detergents are used, care should be taken to select detergents that are compatible with polypropylene, stainless steel and phenolic materials. The reel should not be submerged in any liquid, but can be cleaned by wiping with a damp cloth.

If the float becomes covered with silt or mud, remove the bottom "E" clip, slide the float off the shaft and clean both the float and stainless steel shaft. Replace the float with the word "CLOSED" pointing toward the top of the probe and replace the "E" clip.

5 BATTERY REPLACEMENT

Battery Replacement Procedure

Replace the battery when the audible signal and light become reduced in their intensity, as follows:

Step 1
Remove the three screws from the faceplate.

Step 2
Gently pull the faceplate out of the reel. Observe the orientation of the faceplate and the battery.

Step 3
Replace with a new 9 volt DC transistor battery (grasp black connector, not the wires).

Step 4
Position the battery in the notch of the printed circuit board and align the battery with the recessed slot in the bottom of the cavity of the reel.

Step 5
Push the faceplate firmly into place in the reel. The faceplate may have to be rotated back and forth slightly so the battery will drop into the recessed slot in the bottom of the reel.

Step 6
Replace the three screws through the faceplate and into the reel. Again the faceplate may have to be rotated back and forth so the screws will line up with their respective holes.

Step 7
Check for operation as outlined in section 3 of this manual, "Operation Procedure".

Step 8
If the KIR-89 is to be stored for long periods of time while not in use, it is recommended that the battery be removed.

QUESTIONS? Call 1-800-542-5681.

6 WARRANTY & REPAIRS

WARRANTY

The Manufacturer, Keck Instruments, Inc. warrants the equipment manufactured by it, under normal use and service, to be free from defects in material and workmanship under the following terms and conditions:

This equipment is warranted for 90 days from date of shipment from the Manufacturer to the Purchaser except for scintillation probes. The scintillation probe is warranted to be in working order upon delivery to the purchaser.

The warranty is limited to replacement of part or parts which are determined to be defective upon inspection at the FACTORY. Shipment of defective part or parts to the FACTORY shall be at the expense of the PURCHASER. Return shipment of repaired/replaced part or parts covered by this warranty shall be at the expense of the Manufacturer. Unauthorized alteration and/or repair by anyone which causes failure of the unit or associated components will void this WARRANTY in it entirety.

The Purchaser warrants through the purchase of the geophysical equipment that he is familiar with the equipment and its proper use. In no event shall the manufacturer be liable for any injury, loss or damage, direct or consequential, special, incidental, indirect or punitive, arising out of the use of or inability to use the equipment sold to Purchaser by Manufacturer. Before using the equipment, Purchaser shall give the equipment a reasonable and prudent examination and/or tests to determine the suitability of said equipment for Purchaser's intended use, and Purchaser assumes all risk and liability whatsoever in connection therewith from the time of delivery to Purchaser.

Model _____ Serial No. _____ Date of Purchase _____

EFFECTIVE DATE 4/1/90

KECK INSTRUMENTS, INC.

KECK TAPE GUARD

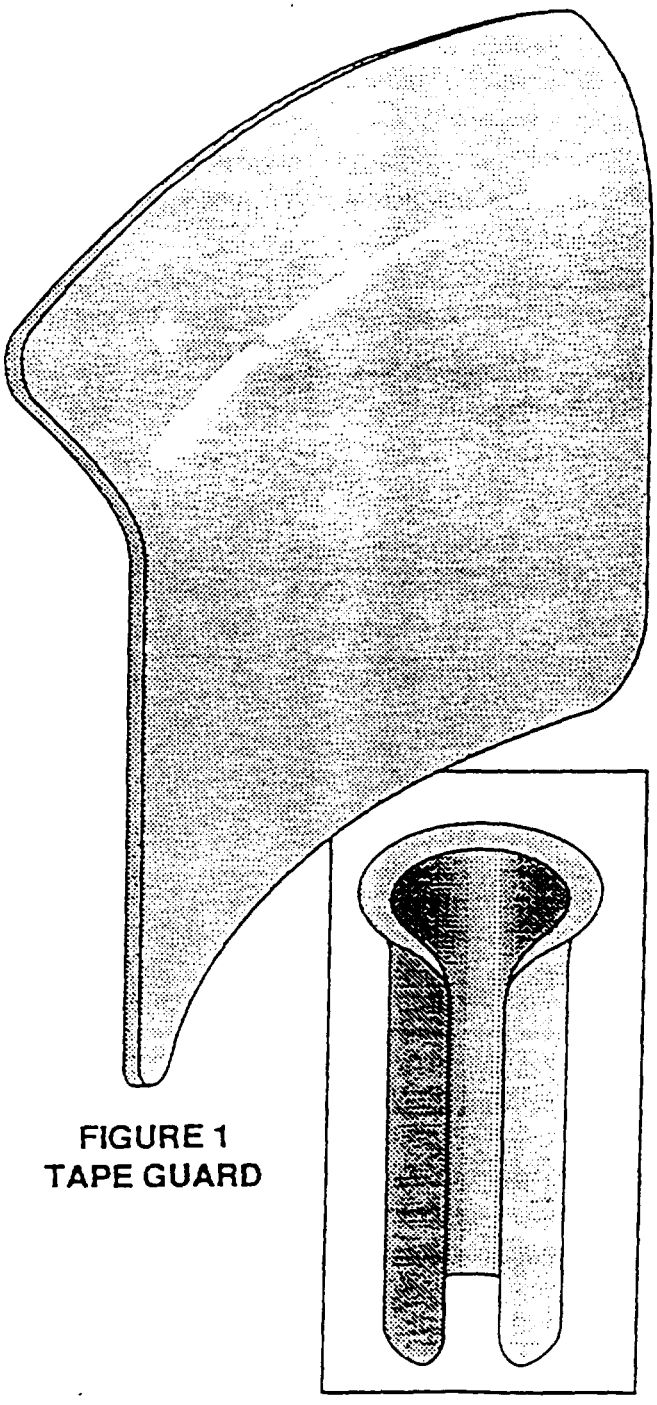


FIGURE 1
TAPE GUARD

The Keck "Tape Guard" was developed to protect instrumentation, tapes and sample tubing from the wearing edges of well casing. Made of smooth flexible polystyrene, the "Tape Guard" easily adapts to any 2" or 4" well.

Instructions

Simply compress the "Tape Guard" and insert

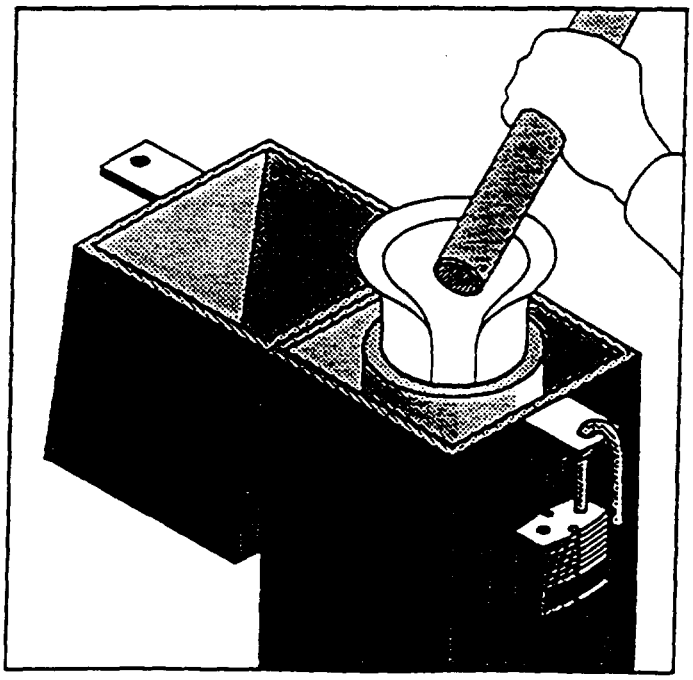


FIGURE 2
TAPE GUARD USAGE

into the opening of any 2" to 4" well pipe. Allow instrumentation, tubing or tape to ride on the smooth surface of the "Tape Guard" to prevent wear.

ATTACHMENT 3

NAPL RECOVERY MODELING USING ARMOS©

ATTACHMENT 3

NAPL RECOVERY MODELING USING ARMOS©
LENZ OIL SERVICE, INC. SITE
LEMONT, ILLINOIS

The recovery of nonaqueous phase liquids (NAPL) from the Lenz Oil site will be simulated by using the Areal Multiphase Organic Simulator (ARMOS©), written and distributed by Environmental Systems and Technologies, Inc., Blacksburg, VA. ARMOS© is capable of simulating: (1) the migration of separate-phase, lighter-than-water NAPL in unconfined aquifers under natural gradients during and following a spill or leakage from storage facilities; (2) the recovery of NAPL from trenches or networks of recovery wells in order to facilitate the design of remediation alternatives; and (3) the approximate volume of NAPL present at the site. A user's guide is included as Enclosure 1.

For the Lenz Oil site, only the volume of NAPL present and the recoverable volume will be determined. The model will calculate the approximate volume of NAPL present at the site by integrating the thicknesses of NAPL in each observation well with the given soil properties. The initial remediation model will include a single pumping well. This well will pump water at a constant rate, while hydrocarbon is skimmed to maintain zero product thickness in the well. The pumping will continue until the recovery rate is very low. The duration of remediation and amount of recoverable NAPL will be determined at this point. Additional wells may be added to the model based upon the extent of the NAPL.

ARMOS© calculates fluid table elevations and the total, free and residual oil volumes per unit area for each specified node at prescribed time intervals. Fluid table elevations are given at user-specified "observation well" locations. Output for each recovery well includes location, water and NAPL pumping rates, cumulative water and NAPL recovery, and well fluid levels. For each output period, the cumulative change in oil

volume, area of soil with free NAPL present and area of soil with residual or free NAPL present are also calculated.

The input data for ARMOS© include:

- Initial conditions such as elevations of air-oil and oil-water interfaces;
- Prescribed boundary conditions;
- Soil properties (see Table 1);
- Fluid properties (see Table 2); and
- Run-time parameters such as mesh data, time increments and convergence criteria.

Initially, the model will include a steady-state aquifer condition, where the boundary conditions of head will be fixed at elevations equivalent to averge conditions measured during the RI. The average water table hydraulic gradient of 0.0035 determined during the RI (page 3-22) will be induced from these boundary conditions.

The fluid properties required by ARMOS© will be determined by using data collected during the field sampling to determine the extent and characteristics of the NAPL and previously collected from the remedial investigation (RI), and the soil properties will be

taken from data collected during the RI (ERM-North Central, 1993). Because soil properties may vary spatially, a range of these properties within the area of concern will be modeled to evaluate the sensitivity of the model to these parameters.

For the Lenz Oil site, grain size analyses are available for soils obtained from the MW-5 and MW-4 borings. This information will provide a basis for inputing soil grain size into the model. The input parameters for soil properties necessary to run the ARMOS© model are included in Table 1. The ARMOS© model will calculate the soil parameters shown in the table as "TBD" from the grain size analyses.

The known hydraulic properties of the NAPL and water are presented in Table 2. Verification and final selection of the NAPL characteristics will be made from data collected during the investigation. The parameters shown in Table 2 as "TBD" will also be calculated by the model.

The grid size for the ARMOS© model will include the area over which the NAPL was encountered in the borings advanced during the RI and this investigation. It is anticipated that the model area will be approximately 400 feet long by 400 feet wide.

REFERENCES

Chemical Rubber Company, 1990. Handbook of Chemistry and Physics, 71st edition. CRC Press, Inc.

Environmental Science and Technology, 1991. Areal Multiphase Organic Simulator for Free Phase Hydrocarbon Migration and Recovery, Users Guide, Version 5.0. ES&T, Inc. Blacksburg, VA.

Environmental Resources Management-North Central, Inc. 1992. Lenz Oil Site Remedial Investigation Report.

Johnson, A. I., 1967. Specific Yield- Compilation of Specific Yield for Various Materials. United States Geological Survey Water-Supply Paper 1662-D.

Vennard, John K., and Robert L. Street, 1982. Elementary Fluid Mechanics, sixth ed. John Wiley and Sons, New York.

TABLES

TABLE 1

VALUES FOR CHARACTERISTIC SOIL PARAMETERS FOR INPUT INTO THE ARMOS© MODEL LENZ OIL SITE LEMONT, ILLINOIS

Parameter	Symbol	Average Value[1]	Minimum Value	Maximum Value	Notes
Total Porosity	ϕ	0.368	0.191	0.57	2
Effective Porosity	ϕ_e	0.20	0.10	0.30	3
Residual Ground Water Saturation	S_{mv}	TBD	TBD	TBD	4
Unsaturated Zone Residual NAPL Saturation	S_{og}	TBD	TBD	TBD	4
Saturated Zone Residual NAPL Saturation	S_{or}	TBD	TBD	TBD	4
Saturated Hydraulic Conductivity	K_{sw}	606 gpd/ft^2	178 gpd/ft^2	4102.5 gpd/ft^2	5
Mean Pore-size (van Genuchten) Parameter	α_v	TBD	TBD	TBD	4
Pore-size Distribution (van Genuchten) Exponent	n_v	TBD	TBD	TBD	4

Key:

TBD = To be determined. See the text and the model's users' guide for an explanation of how these parameters will be calculated.
RI = Remedial Investigation.
NAPL = Nonaqueous phase liquids.

Notes:

(1) Geometric mean as calculated from data presented in the RI.
(2) Values based on Lenz Oil geotechnical testing presented in Appendix J of the RI.
(3) Values obtained from Johnson (1967).
(4) To be determined empirically from equations described in ES & T (1991).
(5) Values based on Lenz Oil hydraulic conductivity testing presented in Appendix I of the RI.

TABLE 2

VALUES FOR CHARACTERISTIC NAPL PARAMETERS FOR INPUT INTO THE ARMOS© MODEL LENZ OIL SITE LEMONT, ILLINOIS

Parameter	Symbol	Average Value	Minimum Value	Maximum Value	Typical Value	Notes
Ratio of NAPL to Ground Water Density	ρ_{ro}	0.875	0.87	0.88	0.90	1,2,3
Ratio of NAPL to Ground Water Kinematic Viscosity	μ_{ro}	22.3	14.43	30.1	7.20	1,2,3
Ratio of Water Surface Tension to NAPL Surface Tension	B_{ao}	TBD	TBD	TBD	2.50	1,4
Ratio of Water Surface Tension to NAPL Water Interfacial Surface Tension	B_{ow}	TBD	TBD	TBD	1.80	1,4

Key:

TBD = To be determined. See the text and the model's users' guide for an explanation of how these terms will be determined.
RI = Remedial Investigation.
NAPL = Nonaqueous phase liquid.

Notes:

(1) Typical values are from ES & T (1991), CRC Handbook of Chemistry and Physics, 71st Edition, and Elementary Fluid Mechanics (Vennard & Street, 1982).
(2) Value obtained from RI sample results of oil as reported on page 4-24 of the RI.
(3) The final value is to be determined during the field investigation to determine the extent and characteristics of the NAPL.
(4) Will be calculated by the ARMOS© model.

ENCLOSURE 1

ARMOS© USER'S GUIDE

A R M O S ©

Areal Multiphase Organic Simulator

for Free Phase Hydrocarbon Migration and Recovery

User and Technical Guide

Environmental Systems & Technologies, Inc.
2701 Ramble Road, Suite 2 • Blacksburg VA 24060 U.S.A.
703-552-0685 • 800-926-5923 • BBS 703-951-8286 • Fax 703-951-5307

Table of Contents

1. Getting Started with ARMOS

1.1 Introduction

ARMOS (AReal Multiphase Organic Simulator) is a numerical model to simulate flow of water and/or hydrocarbon in an unconfined aquifer. ARMOS can simulate leak events of specified rates, durations and locations to facilitate forensic investigations or to evaluate monitoring strategies for storage facilities. Water injection at point sources as well as spatially distributed natural or induced recharge may also be simulated. ARMOS can model multiple recovery wells or trenches with free product skimming with or without water pumping.

ARMOS simulates areal movement of water and free phase hydrocarbon under natural gradients as well as under conditions involving hydrocarbon skimming with or without water pumping to evaluate environmental impacts of hydrocarbon releases and to compare alternative remediation measures. Travel paths and travel times for hydrocarbons spills or leaks can be predicted to assess the behavior of an immiscible plume for use in advance planning, for control and remedial design or for resolution of litigation issues. Due to the high cost of recovery and control operations, and the substantial costs that can result from inadequate system operation, optimization of remedial system designs can provide major cost savings. Application of the model during the early stages of a major remediation effort may be undertaken to provide guidance on remediation system design to locate recovery wells and to determine optimum operating conditions. ARMOS may be used to optimize the number and location of product recovery wells and pumping rates for oil and water, predict the performance of remediation systems for subsequent economic analysis, monitor system performance by comparison of observed and simulated behavior to provide early warning of possible operational problems, and to provide input for regulatory decisions.

The modeling approach in ARMOS is based on the concept of vertical equilibrium pressure distributions analogous to the Dupuit-Forsheimer assumption of conventional groundwater hydrology. This approach reduces the highly nonlinear three-dimensional multiphase flow equations to a mildly nonlinear two-dimensional prob-

lem. The result is a practical, yet physically rigorous model for areal flow of water and free product.

ARMOS can model the migration of separate phase lighter-than-water hydrocarbon under natural gradient conditions during and following a spill or leakage from subsurface storage facilities – subject only to the limitation that vertical flow through the unsaturated zone is not explicitly considered. ARMOS can also simulate recovery of hydrocarbon from trenches or networks of recovery wells to facilitate design of remediation schemes.

Unlike vertical equilibrium models which assume a sharp oil-water interface in the soil, ARMOS describes soil capillarity with a general model that is applicable to fine as well as coarse grained soils. The model gives full consideration to the retention of residual hydrocarbon in the unsaturated and saturated zones, associated with changes in fluid table elevations over time, which are of great practical significance.

ARMOS provides options to model simultaneous transient flow of water and hydrocarbon; to model hydrocarbon flow only with steady-state water flow to reduce computational effort when appropriate; or to model water flow only to facilitate model calibration. ARMOS Version 5.0 utilizes a very efficient iterative solver on a reduced matrix modified to eliminate oil-free nodes.

Input data for ARMOS include initial conditions prescribed as elevations of air-oil and oil-water fluid tables, prescribed boundary conditions, soil properties, fluid properties and run-time parameters such as mesh data, time increments and convergence criteria. Fluid properties required by ARMOS are the viscosity, density and surface tension of the hydrocarbon. Soil properties include the saturated hydraulic conductivity and parameters defining the saturation-capillary pressure-relative permeability relations. Soil properties can vary spatially and may be anisotropic.

Initial conditions in ARMOS are specified in the Pre-processor using one of several options 1) block edit– to enter nodal values for product thickness and depth to water, 2) measurement points– to krige initial fluid table elevations from monitoring well data, 3) retrieving levels from the database, 4) or restart from a previous run. Boundary conditions can be stipulated as prescribed fluid table elevations or fluid fluxes. An option is provided to automatically fix water levels around the perimeter equal to the initial levels or to impose a spatially uniform fluctuation in time via a single water table fluctuation schedule. Alternatively, the user may specify arbi-

trary schedules for time varying water or oil elevations or fluxes on boundaries in a very general fashion.

Water pumping in ARMOS may be specified by the pumping rate or the pump intake elevation, or a combination (*i.e.*, if the water level drops below the intake elevation for the specified rate, the level will be fixed at the intake elevation). Partial penetration of wells in an aquifer is approximated by using a reduced water transmissivity at the well.

The output from ARMOS gives predicted fluid table elevations, total, free and residual oil volume per unit area and water and oil velocities for each node at prescribed printout intervals. At user-specified observation locations, fluid table elevations may be produced. For recovery well locations; water and oil pumping rates, cumulative recovery, water and hydrocarbon pumpage and well fluid levels are calculated. For each output time, the cumulative change in oil volume (computed by areal integration and from boundary fluxes) and the area of soil with residual or free oil present are also computed.

Water velocities and oil distributions from ARMOS may be used by the program SpillTrans to model dissolved plume migration and remediation.

ARMOS Version 5.0 is an interactive program designed to run under DOS or Microsoft Windows®. The package consists of two main programs:

A screen format similar to Microsoft Windows® allows you to enter data easily and quickly view results.

- PreArm– a pre-/post-processor that interactively creates data files for the numerical model through a graphical user interface and allows you to directly view model output.

- RunArm– the actual executable numerical model that provides run-time output of fluid levels, volumes and pumping rates over time.

The ARMOS User and Technical Guide is organized as follows.

The remainder of Chapter 1 focuses on hardware requirements, installation procedures, and information on technical support available to ARMOS users.

Chapter 2 discusses the database and graphics components of ARMOS.

Chapter 3 provides a detailed description of the operational features of the pre/post-processor and practical comments on its use.

Chapter 4 details the mathematical model and numerical methods used by ARMOS.

Chapter 5 covers the soil and fluid properties required to run ARMOS and practical parameter estimation methods.

Chapter 6 presents applications of ARMOS to hypothetical and actual field problems designed to evaluate program accuracy and demonstrate its practical use.

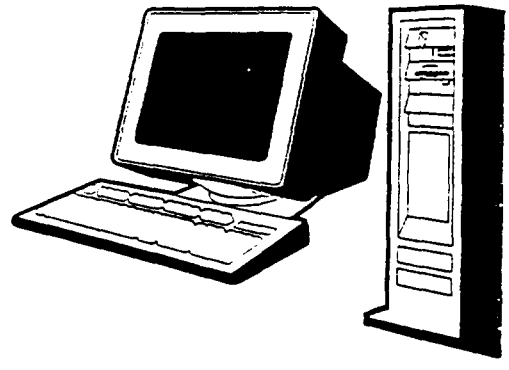
The tutorial exercise in Chapter 7 steps you through the program for a typical ARMOS problem.

1.2 Quick Start

If you want to jump into the program right away for a quick look at its capabilities, we suggest that you first finish reading this chapter to ensure proper installation of the program and to understand the notation used in the manual. Then take a test ride by stepping through the tutorial described in Chapter 7. You still need to read through the manual thoroughly before doing any serious work to be sure you understand all of the program's capabilities.

1.3 System Requirements

- Personal computer based on an Intel 80386 processor or higher
- Numeric co-processor (Intel 80387 or better)
- 8 MB of RAM, 7 free MB of EMS, XMS, or extended memory.
- 12 MB free hard disk space
- VGA graphics card or better
- MS-DOS or PC-DOS operating system version 4.01 or higher, and/or Windows®
- Microsoft or compatible mouse
- Dot matrix or laser printer with graphics capability
- Site map in DXF format (Optional). Map must be readable by AutoCAD version 10, 11 or 12.
- If EMM386.EXE is used, be sure you do not use the **noems** switch. Also, ARMOS requires that you specify a minimum value of 1MB for EMS, if EMM 386 is to be used.



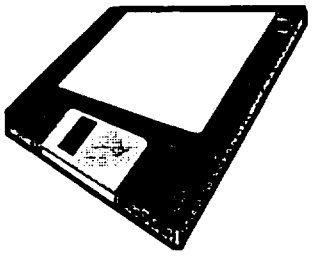
1.4 Notation Review

Whenever you are told to "click on" or to "select" an item, locate the mouse cursor over your selection and click the left mouse button. Throughout this manual, command sequences are in bold, and "buttons" (areas on the screen that look like buttons that can be "pressed" using the mouse) are in bold surrounded by brackets [].

Therefore you would read the sequence "**Database / Data Entry / Soil Bore / [Insert]**" as click on "**Database**", "**Data Entry**", and "**Soil Bore**", in sequence as they appear in the menus, followed by clicking on the "**Insert**" button.

Keyboard strokes are in bold and surrounded by "< >". For instance, the "Enter" key on your keyboard is represented as **<Enter>**.

1.5 Installation



Insert the ARMOS disk into the floppy disk drive on your computer. We assume this is your "A:" drive, but if it is not, simply replace "A:" with the relevant drive designation (for example, "B:") in the following instructions.

For a DOS install:

Type **a:** and press **<Enter>**. When the A:\> prompt appears, type **install** and press **<Enter>**. You are asked to enter the drive where you want ARMOS installed. Enter the hard disk id (e.g., C:). The install utility creates a subdirectory called **\est** in the drive you indicate if one is not already present. For example, if you type **c:** the program installs in the directory **c:\est.**

For a Windows® install:

From the Windows® Program Manager select **File / Run**. Type **a:\install**. This will open a DOS window with the initial install box. You are asked to enter the drive where you want ARMOS installed. Enter the hard disk id (e.g., C:). The install utility creates a subdirectory called \est in the drive you indicate. For example, if you type **c:** the program installs in the directory **c:\est.**

The current install program does not allow for a Windows® group to be written, so that if you own SpillCAD, or other ES&T software, your current Windows® setup will not be overwritten. If ARMOS is your first ES&T program you will need to create a new group and place the PreArm and RunArm icons within it. To create the group file go to **File** in your Program Manager and select **New**. Choose **Program Group**, then press **[OK]**. The Program Group Properties dialog box will ask you for a description and a group file. You may enter anything you wish for the description, usually something that will remind you that this group file contains PreArm and RunArm. Beside group file, type **es&t**. Once you have created the group file, you can place icons for RunArm and PreArm inside of it. Select **File / New** from your Program Manager. Now select Program Item. You will need to browse to the **est** directory, then select **pre-**

arm.exe. Next you will have to change the icon. Click on **[Change Icon]**. A note will pop up about selecting from progman. Click on **[OK]**. This brings up a list of icons in **progman.ini**. Click on **[Browse]** and go to the **est** directory. From here select **prearm.ico**. Lastly, you will need to add RunArm. Follow the procedure above for PreArm, though without changing the icon, since it is imbedded in the program.

Your program license is supplied on a hardware device called a "MemoPlug". The MemoPlug must be plugged into one of the parallel printer ports on your computer. You can connect a printer in series with the MemoPlug, which will not effect normal printer operation. If you are going to run ARMOS on a network, you must attach the MemoPlug to the computer on which ARMOS will run. The program and data may reside on any network accessible drive.

If you do not attach the MemoPlug, ARMOS reverts to a demo version in which case database changes are not recorded, model output is not written to disk, and the only project that you can open is the tutorial problem. You can install ARMOS on as many computers as you wish. You can also move the license from computer to computer simply by moving the MemoPlug. Utilities are described in the following section that enable you to transfer licenses from one MemoPlug to another if you have more than one.

Be sure not to lose your MemoPlug, since it can only be replaced by direct exchange with your original plug!

To run ARMOS, change the active directory to the one in which ARMOS has been installed, using the DOS CD command. For example, type **cd c:\est**, then type the command **armos5**. This takes you to ARMOS's opening screen. In Windows® simply double-click on the RunArm icon.

IMPORTANT: ARMOS has been found to be compatible with several memory resident programs (including data compression software, network operating systems and the screen capture software used to create the graphics in this document). However we cannot guarantee that ARMOS will be compatible with all memory resident programs. Occasionally, users have had problems starting or operating ARMOS because a poorly behaved or incompatible TSR (terminate and stay resident) program was loaded in memory. If you have problems starting or running ARMOS, you may need to edit your configuration files (CONFIG.SYS or AUTOEXEC.BAT) to remove possible offenders. Please contact ES&T if you need assistance.

1.6 MemoPlug Utilities

ShowMe utility

The ShowMe utility provided with ES&T software products is a utility for displaying programs or program versions which are licensed to run on a given MemoPlug.

To run this utility, type **showme** at the DOS prompt.

ShowMe displays the information encoded on the MemoPlug. The information provided includes the unique plug number assigned by ES&T, the company to whom the plug is licensed and the software that is licensed from ES&T including code names, version numbers and the serial numbers of the licensed software.

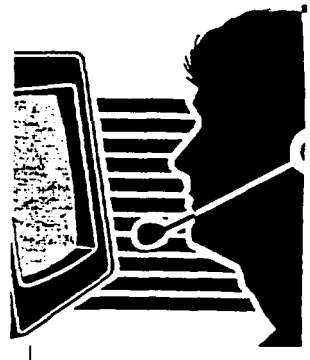
MoveCode utility

To avoid the need to change plugs if you want to run more than one of ES&T's programs on a computer, you can install up to six licenses on a single MemoPlug, using the MOVECODE utility. This allows you to run all of the licensed codes without having to switch plugs. You may move licenses among MemoPlugs in any combination and as many times as you wish.

To move an application from one MemoPlug to another do the following: 1) Install on your computer the MemoPlug that has the license you wish to move. 2) Type **movecode** from the DOS prompt– MOVECODE displays a menu of licenses from the attached MemoPlug. 3) Select the numbers of the license(s) you wish to move. 4) Replace the current MemoPlug with the destination MemoPlug. **DO NOT TURN THE POWER OFF, REBOOT, OR EXIT THE PROGRAM during this step or you will lose the license for the code you are moving.** 5) Press any key on the keyboard and MOVECODE transfers the license to the new MemoPlug.

1.7 Technical Support Bulletin Board Service

ES&T provides a free electronic bulletin board service (BBS) for its customers. Using the BBS can greatly reduce the response time required to receive technical support from our staff. Through the BBS, you can ask questions about your particular software product, send data that would normally require mailing a diskette to ES&T, receive fixes and updates to software in a timely manner, and exchange ideas with other users.



To use the BBS you will need:

A modem with a communication speed between 1200 and 19,200 bits per second.

Communications software such as Procomm, Crosstalk, Qmodem, Telix, or similar software with the following capabilities:

- ANSI-BBS, VT10x or TTY terminal emulation
- Xmodem or Ymodem file transfer protocol for sending and receiving files

1.7.1 Connecting with the BBS

Load your communications software. Configure your software to use the communications parameters of no parity, 8 data bits, and 1 stop bit (N,8,1) or even parity, 7 data bits and 2 stop bits (E,7,2). Now instruct your communications software to dial the ES&T customer support BBS at (703) 951-8286. You will be asked for your User ID. If you are calling for the first time type **New** as a response. If you are new the system will then ask you a series of questions to help identify you and assign you a new user ID and password. Please remember your password, you will not be able to access your ID in the future without it. After entering your user ID and password you will be placed at the main menu of the BBS.

1.7.2 Electronic mail

To leave a message on the BBS for the ES&T technical support staff you will need to use electronic mail (e-mail). E-mail allows you to send and receive private messages with ES&T personnel. In addition, electronic mail allows you to submit problem data files and other forms of information that can be of use in solving your particular problem. To utilize the e-mail facility, select **E** from the Main Menu. From here, you may read e-mail addressed to you or send e-mail to another user on the system. To exit the e-mail system you may press **X** at any of the e-mail prompts and you will be returned to the main menu.

Writing an e-mail message

Select **W** to write an e-mail message. You will be asked for the User-ID or Special Interest Group (SIG- see Section 1.7.3) to whom to send a message. If you know the ID of the person you are sending the message to enter it at the prompt. If you are unsure of whom to send your message to, or do not know, press **<Enter>** and mail it to the system operator (SYSOP). The system operator will route it to the appropriate person within ES&T. You will then be asked the message topic. This should be a brief description of what the message is about. After this you will be placed in the message editor in which you can type in your message. When you are done, you can type **OK** on a line by itself to edit or abort the entry of the current message. If you do not need to edit your message you can type **/S** on a line by itself to save the message without editing. If you choose to save your message you will then be asked if you wish to "attach" a file to this message. This is useful if you want send a dataset to our technical support staff to review. If you need to send a file, answer **Y** to the question and follow the prompts for attaching a file to your message.

Reading an e-mail message

To read your e-mail, select **R** from the E-mail menu. This selection allows you to read e-mail that was sent by another user to you or to review the e-mail you have sent. To read mail addressed to you, select **T** at the next prompt. When prompted for the message number press **<Enter>** to start at the first message, you will then be shown the message subject and given an opportunity to read the message or continue searching if you do not wish to read a particu-

lar message. To read a given message select **R** and the text of the message will be displayed. When you are done reading e-mail, enter **X** at every prompt until you are at the main menu.

1.7.3 Code technical support

Environmental Systems & Technologies sells a number of Modeling Software packages. To provide updates, fixes and new releases a Special Interest Group (SIG) has been set up for each product. Each SIG is devoted to information about a specific product. To get to the SIG for a particular product, select **C** from the main menu. You are placed in the /Hello SIG, which is the default SIG. From there select the specific SIG (explained below) you want to access (join). Within each group you can read bulletins/messages, write bulletins/message and download files.

To access (join) a new SIG, select **S** at the SIG prompt to select a new SIG. You are then prompted to enter the name of the SIG you wish to access. If you do not know which SIGs are available enter **?** for a list of available SIGs. After the list has been displayed you are given another chance to enter the name of the SIG you wish to access.

1.7.4 Downloading a file

To receive updates, fixes and revisions from the BBS you need to download a file. Downloading is the process of transferring a file from the BBS to your computer. To download a file select **D** from the SIG menu. This will allow you to search through the SIG bulletins for files that you might want to download. You can perform a keyword search, scan through the file list or get a full listing of the files available. In this case, select **S** to scan through the files. Once you have found the file you wish to download, remember the bulletin number it is attached to so that you can later read the bulletin and actually transfer the file. After you have found the file you want, press **X** to get back to the SIG menu. Then select **R** to read the bulletin with the file you want to download. At the prompt enter the bulletin number you wish to read. The BBS will respond with a short description of the bulletin. Select **R** to read the bulletin. Performing this action will give a more detailed description of the file followed by a prompt to download the file. Answer **Y** at the download prompt. You will then be asked for a transfer protocol. Select the appropriate protocol for your communication software.

WARNING: binary files cannot be transferred using the ASCII protocol. It is generally safe to select either Xmodem or Ymodem. If your software supports Ymodem, file transfers will be about 25% faster than using the Xmodem transfer protocol. After you have selected the file protocol, instruct your communications software to start receiving a file and select the same protocol that you told the BBS to use. The BBS will then transfer the file to your system.

In order to use files downloaded from the BBS you need the latest version of PKZIP and PKUNZIP. If you do not have these you can download them from the /HELLO SIG. Do this by downloading the executable file (pkz204g.exe) that contains PKZIP and PKUNZIP (a descriptions follows every file on the BBS). After this executable file is downloaded, type the file's name at your C:>. The use of PKZIP and PKUNZIP programs reduces the time necessary to transfer files to and from the BBS often by as much as 75%.

Using PKUNZIP

To use a file downloaded from the BBS type PKUNZIP followed by the name of the file you downloaded from the ES&T BBS. An example using PKUNZIP is shown below:

```
C:\PKUNZIP foo.zip
```

PKUNZIP will then extract the files contained within the archival file for your use.

Using PKZIP

When you need to send a file or group of files to ES&T, it is best that you "zip" the files into an archive. This process has two main advantages. First, the time necessary to transfer data to the BBS is greatly reduced. Secondly, if your problem has multiple files, they will be packaged into a single file that can be uploaded with less effort. An example using PKZIP is shown below:

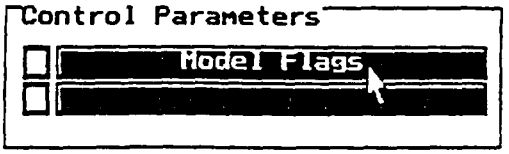
```
C:\PKZIP foo.zip *.arm
```

This command creates an archive file called foo.zip that contains all of the files ending in the .arm extension in the current directory. Instead of manually uploading each .arm file you can just upload the foo.zip file in its place.

Getting Around in ARMOS

1.8 Using a Mouse

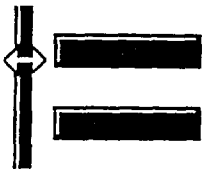
Roll the mouse around on your desk and you will notice the small arrow moving around on the screen. This is the mouse pointer (also referred to as the mouse cursor). You use the mouse pointer to select items from the screen.



1.8.1 Clicking

Throughout this documentation you will see the terms "click on" and "select". Both of these refer to a specific mouse action. When you are told to click on or select an item, locate the mouse cursor over the selected item and press the left mouse button.

1.8.2 Dragging



You can use the dragging technique to move or resize windows. To drag an item, locate the mouse cursor over your selection, then press and hold down the left mouse button. Move the mouse to make your adjustment, then release the left mouse button.

1.9 Using PreArm's Windows

The ARMOS Pre-processor (PreArm) operates under DOS or under a DOS window, and presents the user with a graphical "windowed" environment similar to that of Microsoft Windows®. We describe below the elements of a window, using the main screen of ARMOS as an example. More detailed descriptions of some features, such as the scroll bar, are given later.

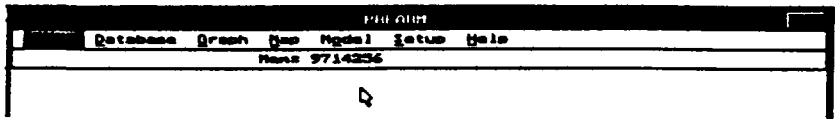
Title bar

The title bar shows the window title. If more than one window is open, the title bar for the active window is a different color and intensity than other displayed title bars.

Menu bar

The menu bar lists the available menu items. In Figure 1, the menu bar includes **File**, **Database**, **Graph**, **Map**, **Properties**, **Model**, **Setup**, and **Help**. This particular menu is referred to as the "main menu" throughout this document.

Figure 1



If you like to use a keyboard more than a mouse, you can navigate the Pre-/Post-processor by using **<alt>** and the underlined letter of the menu choice you want. For example, if you want to select Query under Database type **<alt> d q** and the Query engine opens.

Status line

The status line is located directly below the main menu. It displays the bytes of free memory and a continuous readout of the X and Y coordinates of the mouse pointer's location on the workspace map in drawing units (the units used in the DXF site map). Sometimes messages are also displayed on the status line.

Scroll bar

Scroll bars let you scroll up and down through a list to move parts of a list into view when it is too long to fit in the allotted space. (See Section 1.9.3).

Window border

The window border is the outside edge of a window. You can adjust the size of a window by dragging the border. Alternatively, you can drag the window corner to shorten or lengthen two sides of a border at the same time. (See Section 1.9.4).

Workspace

The workspace is where you do your work (that is, you can bring into view and work with maps, tables, etc. here). Often you will have more than one window open in this space.

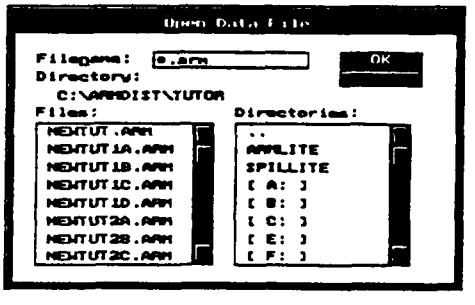
Selection cursor

The selection cursor marks the place where text or graphics will next appear when you begin typing or drawing.

1.9.1 Dialog Boxes

Dialog boxes request or provide information, but do not have menu bars. For example, a dialog box will appear on the screen after you select **Model** from the ARMOS main menu and **Pre-processor / Open** from the drop-down menu. This is the Open Data File dialog box (Figure 2).

Figure 2



The field in the dialog box for your next input will contain a flashing square cursor (called the "selection cursor"). Any information typed into this field will replace all previous information. You may use the Delete or Backspace keys to clear the space first if you wish, or to correct input errors.

To move to a different field within the dialog box, click anywhere in the new field. You may also use the Tab key, the Shift-Tab key combination, and the arrow keys to move from field to field.

If at any time you wish to escape from the dialog box WITHOUT SAVING any of your changes, click on **[Cancel]**, **[Close]**, or **[Exit]**, depending on the dialog box button options available. ARMOS will return you to the workspace and the most recent main menu selection will be highlighted.

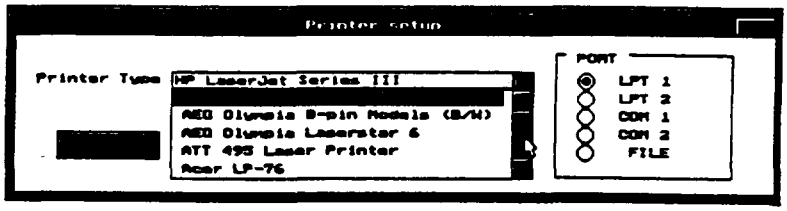
To proceed after you have supplied all of the information requested in the dialog box, select **[Save]**, **[OK]**, **[Accept]**, or **[Done]** depending on the dialog box button options available.

ARMOS occasionally uses dialog boxes to display warnings or additional information, such as a reminder that you must provide some missing data in order to perform a calculation.

1.9.2 List Boxes

A list box is a specialized dialog box which provides a list of available choices from which you must make a selection (or cancel). For example, selecting **Setup / Printer** from the ARMOS main menu will open a list box with several printer choices (Figure 3).

Figure 3



If a list is too long to view in its entirety, you may use a scroll bar to move up and down through the list. (see Section 1.9.3).

To select an item from a list, move to the desired item and click the left mouse button. The appropriate field is automatically updated. To change your selection (if you made an error in your original selection, for example), you can return to the list and make a different selection.

1.9.3 Scroll Bars

Some dialog windows and dialog boxes have scroll bars you can use to view lists that require more than the available space.

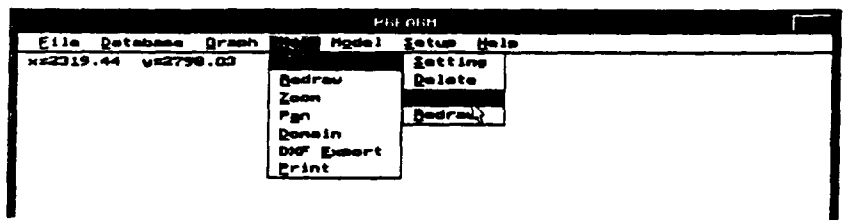
To scroll information line by line, click repeatedly on one of the scroll arrows until the desired information comes into view. Alternatively, to page through the list quickly, click the scroll bar above or below the scroll box on the vertical scroll bars, or drag the scroll button up or down the scroll bar.

1.9.4 Menus

The menu bar at the top of each window lists the commands available for that window.

All menu items in the ARMOS main menu (**File, Database, Graph, Map, Model, Setup,** and **Help**) will open another menu. These "drop-down menus" list additional menu choices relevant to the main menu item (Figure 4).

Figure 4



Some menu items in the drop-down menus will open additional drop-down menus. For example, the selection sequence **Map / Overlay** will produce a second drop-down menu (Figure 4) which will in turn allow you to open a dialog box. Any number of drop-down menus may exist, but eventually selection of a menu item will result in the desired task being executed or calculation being performed.

To remove all menus from your screen, except the main menu, move the cursor to any point in the workspace outside of the menu(s) and click the mouse, or press **<Esc>**.

1.10 Using Help

On-line help is available throughout ARMOS. Where help is available, it is accessible either from the active menu or from a selection button. To bring help information into view, click on the word "Help" in the active menu, or click on the **[Help]** button.

You can exit Help at any time by selecting **[Close]** from the Help window menu bar.

2. Database and Graphics Features

2.1 Introduction

The heart of the ARMOS Pre-/Post-processor is its graphical database. Locations of monitoring wells and soil borings are identified on a site map that you can view at any scale. You can import site maps from common CAD drawing programs; enter data in a spread-sheet-like environment and perform queries to extract data to plot or to identify locations and times when data meet certain criteria. For example, if you want to know which wells have exhibited product thickness greater than 1 foot between certain dates, you can extract these values from the database and display them on the site map.

You can view spatial data as point data, draw contour plots and store the displays as overlays to view on the site map. You may also add or delete overlays from the map as needed to evaluate relationships among variables or to improve clarity.

You can ask ARMOS to produce time series and other X-Y graphs from query results to view well hydrographs, concentration histories, or trends and relationships among any variables stored in the database.

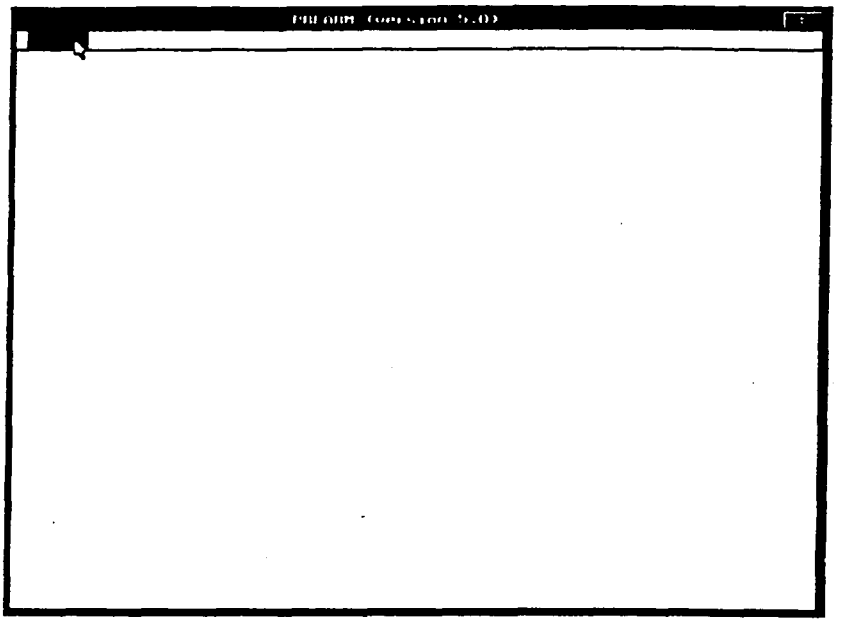
In this chapter, we describe the features of the Database, Map and Graph functions in ARMOS. Chapter 7 contains a tutorial that steps you through these functions for an example problem.

2.2 Project, Database and Map Names

Each time you begin a session with ARMOS, the main menu displayed on the initial screen will have only one menu item - **File** (Figure 1). Place the mouse cursor on **File** and click the left mouse

button. This produces a drop-down menu with three choices: **Project**, **About** and **Exit**.

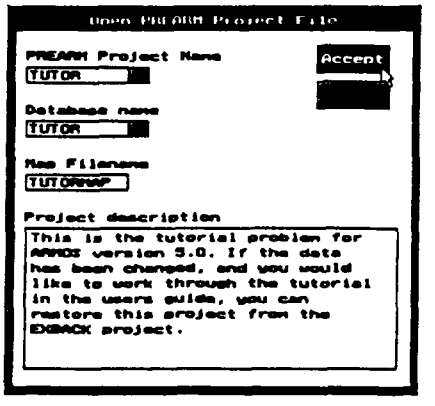
Figure 1



Selecting **About** gives you information about ARMOS. Selecting **Exit** terminates the program, returning you to DOS or Windows®.

To open a new or existing project, select **Project / Open**. A dialog box appears with fields for entering a project name, database name, map filename, and project description (Figure 2).

Figure 2



If you want to open a *new* project, type in a new **project name**. If you want ARMOS to use an existing database rather than create a

new database, you may enter an existing **database name**. This allows you to use one database for more than one ARMOS project. Note that ARMOS assumes that any **database name** which is different from your project name is an already existing database. In other words, you cannot create a new database file with a name that is different from your project name. If the **database name** field is left blank, ARMOS creates a project database with the same name as your project.

If you have a site map in a DXF-format file, type in the **map file** name. The DXF map must be in the ARMOS Pre-processor directory. A map is not required to run the ARMOS Pre-processor, but is helpful for visualizing well configurations and spatial distributions of measurements or model output.

To open an *existing* project, type in the **project name** or click on the down arrow button on the right side of the Project Name box to display a list of existing projects. It is not necessary to type in database or map names since ARMOS remembers database and map names associated with each project. The exception is when you want to use a different (but already existing) database or map than previously used with the project.

Regardless of whether you are opening a new or existing project, you can edit the **Project Description** (limited to 255 characters) which is saved when you select **[Accept]**. Selecting **[Accept]** loads the selected project, database, and optional project map. In the case of a new project, a message box appears with the message "Project not found". Click on **[Create]** to prompt ARMOS to create a new project. If you did not intend to open a new project (for example, you may have misspelled the name of a previously existing project you were trying to open), click on **[Re-enter]** to return to the Open ARMOS Project File window, and enter the correct project name.

To delete a project, select **Project / Delete**. A dialog box appears with a field for entering the name of the project you wish to delete. ARMOS allows you to only delete projects which are not currently open. Again, you can click on the down arrow button on the right side of the **project name** box to display a list of existing projects. Type in or select the **project name** and select **[Accept]** to delete that project. A warning appears, giving you one last chance to **[Cancel]** the delete operation, or to proceed by clicking on **[Delete]**. After pressing either, ARMOS returns you to the main menu.

Two additional menu selections are available under **File / Project** once you have opened a project– **Save as** and **Save**. **Save as** allows you to save the currently open file under a new name. You may, for example, want to experiment with some changes to an existing project without having to change everything back when you are through experimenting. Or you may want to start with an existing project and edit it to set up a new project. You can accomplish both by opening the existing project, then using the **Save as** function to save the project file under a new name. When you implement **Save as**, ARMOS automatically closes the previously opened file, and leaves the newly named project as the open project.

If you decide not to proceed either with opening or deleting a project after you have already opened the corresponding dialog box, select **[Cancel]**. ARMOS returns you to the main menu.

2.3 Database Operations

The ARMOS database allows for entry and manipulation of field data. From within **Database** you can enter descriptive data for monitoring wells and soil borings, soil concentrations from soil borings, and fluid level data and groundwater concentration data collected from monitoring wells.

ARMOS is currently made up of 6 distinct databases. These include a database for Measurement Locations, Monitoring Wells, Soil Borings, Fluid Levels, Soil Concentration, and Ground Water Concentration data.

The Measurement Locations database serves to associate a spatial point with a measurement device. The Monitoring Well and Soil Borings databases define attributes of wells and soil borings, such as top and bottom elevations. Fluid Level and Groundwater Concentration databases define time-dependent records of measurements from monitoring wells and the Soil Concentration database defines records of measurements from samples for soil borings at specified depths.

When you create a new project, ARMOS takes the six character name entered and uses it for each of the new databases. The project name is prefixed with two letters for each of the databases; LC for locations, MW for monitoring well data, SB for soil bore data, FL

for fluid levels, WC for groundwater concentration, and SC for soil concentration data.

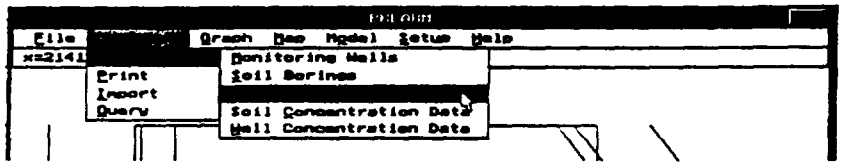
For example, with a project name of TUTOR, the locations database would be LCTUTOR.DB for the actual data and LCTUTOR.PX for the associated index.

In addition to data entry, you can send databases to the printer and query the database (see Section 2.3.4).

2.3.1 Data Entry

To enter data into the ARMOS database, select **Database / Data Entry**. Another drop-down menu appears, listing five database files (Figure 3).

Figure 3



All database files in ARMOS are linked to each other through the ID field. The ID can identify a well or a soil boring, but each ID MUST be unique and every well and boring **MUST** have an X and Y location. The ID field is known as a *key field*. This means that all sorting takes place using this field. It is imperative that each X-Y Location is identified by a unique ID. Should you enter a nonunique ID, ARMOS will discard data entered for the duplicate ID(s). **ARMOS does not warn you when this occurs, so it is your responsibility to ensure the integrity of your data.** Note that although each X-Y Location has a unique ID, ARMOS allows you to specify multiple sample depths for soil samples at a given location; to specify multiple measurement dates for monitoring well data; and to specify concentrations for multiple species for each well.

Be sure to enter unique ID's

A list of database files, the fields available in the file, and any default values, limits, and rules for each field follows. **All input variables with a length dimension are in feet.**

Monitoring Wells

ID	Key field. Alphanumeric.
X Location	The map X coordinate (Easting) of a well or boring. Numeric.
Y Location	The map Y coordinate (Northing) of a well or boring. Numeric.
Date Installed	Date monitoring well was installed in MM/DD/YY format. Date.
Top of Casing	Elevation of the top of the well casing (e.g., mean sea level). Numeric.

Soil Borings

ID	Key field. Alphanumeric.
X Location	The map X coordinate (Easting) of a well or boring. Numeric.
Y Location	The map Y coordinate (Northing) of a well or boring. Numeric.
Date Sampled	Date sample was collected in MM/DD/YY format. Date.
G.S. Elevation	Ground surface elevation above mean sea level. Numeric.

Fluid Density

Enter Density Value	Numeric. Hydrocarbon thickness used to calculate the corrected water table (Z_{aw}).

Fluid Level Data

ID	Key field. Alphanumeric.
Sample Date	Date of measurement in MM/DD/YY format.
Top of Casing	Elevation of the top of the well casing (e.g., mean sea level). Numeric.

D_{ao}	Depth from top of casing to oil. Numeric.
D_{ow}	Depth from top of casing to water. Numeric.
H_o	Product thickness in the well computed by ARMOS. Numeric.
Z_{aw}	Corrected water table elevation computed by ARMOS. To obtain meaningful values, you must specify a fluid density in **Database / Data Entry / Fluid Level Data / Density**. Numeric.
Z_{ao}	Elevation of air-oil table (in the well) computed by ARMOS. Numeric.
Z_{ow}	Elevation of oil-water table (in the well) computed by ARMOS. Numeric.

ARMOS computes a corrected water table for wells with free product if you have specified the product density

Soil Concentration Data

ID	Key field. Alphanumeric.
Sample Depth	Distance from ground surface to the midpoint of the soil sample. Numeric.
Species Name	Name of the chemical species analyzed in your soil sample. Alpha-numeric.
Concentration	Soil concentration of the above species in mg/kg. Numeric.
Sample Interval	Length of the soil sample. Numeric.

Well Concentration Data

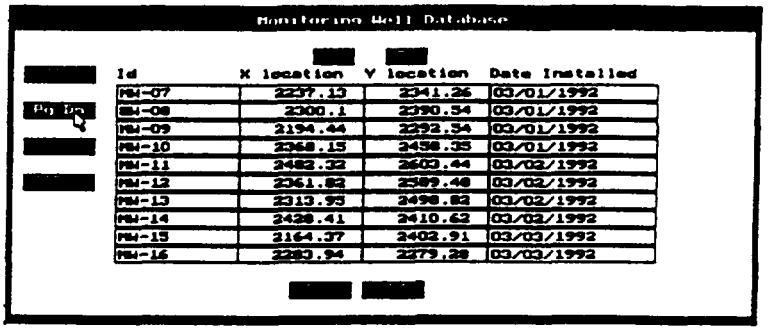
ID	Key field. Alphanumeric.
Sample Date	Date sample was collected in MM/DD/YY format. Date.
Species	Name of the chemical species analyzed in your groundwater sample. Alpha-numeric.
Concentration	Concentration of the above species in mg/l, µg/l, or ng/l. **You must use the**

same units for all data for a single species. Numeric.

The following example (using the **Monitoring Wells** database file) provides you with the basic skills required to perform data entry in any of the databases.

In the tutor file, select **Database / Data Entry / Monitoring Wells / Edit**. A data entry dialog box appears (Figure 4). Use the **[Pg Up]** and **[Pg Dn]** buttons to scroll the data up and down a page at a time. Use the [<] and [>] buttons located above the X Location label to scroll to the right or left. If there are no fields to the right of the displayed data and you click [>], a beep warns you that you can go to the right no further. This occurs when you get to the column **Top of Casing**. Similarly, a beep sounds if you press [<] when the first field is already displayed.

Figure 4



Data are entered wherever the data entry cursor (a small blinking box) is located. To position the data entry cursor, move the mouse cursor to the desired field and click the left mouse button.

To insert a row of data among other non-blank rows, place the data entry cursor on the line below the insertion point. Click on **[Insert]** and a blank row is inserted above the current data entry field.

To enter data on a blank line, position the mouse cursor in the empty ID field and click the left mouse button. A data entry cursor (a small blinking box) appears in the ID field. Enter the appropriate data. Press Enter or Tab to accept the value and to move the data entry cursor to the X Location field. For example, enter the X Location value, press Enter or Tab to move to the Y Location field, and enter the Y Location value.

To delete a line, locate the data entry cursor on any field in the line you want to delete, then place the mouse cursor on **[Delete]** and click the left mouse button.

When you are done entering and/or deleting data, select **[Save]** to save the data or **[Close]** to discard all your changes. Either selection returns you to the main menu.

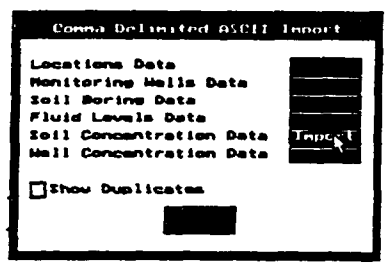
To edit existing data, select the field you want to change, enter new data in its place, then save the changes. **Database / Data Entry / Monitoring Wells / Edit** allows you to move through current data and edit it wherever you need.

2.3.2 ASCII import

Importing a file

Selecting **Database / Import / Comma Delimited** brings you to the Comma Delimited ASCII Import dialog box (Figure 5), or choosing **Database / Import / PRN Format** brings you to the Lotus PRN Import dialog box, which is also an ASCII format. From either you can choose which database you would like to import into. Be sure your file is formatted to conform to the database structure at the end of this section.

Figure 5



Comma delimited files have entries separated by commas and single quotes. For example, a file for monitoring well locations would be set up as **'MW-05','286.34','233.56'** (the first entry is the ID, the second is X location, the third is Y location). Do not place any spaces between the fields. The file would contain the next monitoring well ID, X and Y location on the next line. A list of new monitoring well locations in a comma delimited file might look like this:

'MW-05','286.34','233.56'
'MW-12','251.91','255.6'
'MW-23','202.192','243'
'MW-32','290.634','220.1'

A PRN file is space delimited. The file may have any number of spaces between the data in each column, but, like the comma delimited file, the order must match the database the file is being imported into. For example, the above file would have the following structure:

MW-05	**286.34**	**233.56**
MW-12	**251.91**	**255.6**
MW-23	**202.192**	**243**
MW-32	**290.634**	**220.1**

There may be more or less spaces between columns, and the data may be right or left justified.

When you select a database from the dialog box, ARMOS will prompt you for the file name. When importing data, ARMOS will not overwrite any existing records with the same ID and date. In this case, the message "Key violations, duplicate keys attempted" is displayed. To view the offending records, you can activate the "Show duplicates" option.

Following are the formats of the ARMOS Pre-/Post-processor databases.

The locations database form is:

Name	Type
ID	A10*
X location	N
Y location	N

The monitoring well database form is:

Name	Type
ID	A10*
Date Installed	D
Top of Casing	N

The soil boring database is of the form:

Name	Type
ID	A10*
X location	N
Y location	N
Date Sampled	D
G.S. Elevation	N

The fluid level database form is:

Name	Type
ID	A10*
Sample Date	D*
Top of Casing	N
D_{ao}	N
D_{ow}	N
H_o	N#
Z_{aw}	N#
Z_{ao}	N#
Z_{ow}	N#

The soil concentration database is:

Name	Type
ID	A10*
Sample Depth	N
Species Name	A15
Concentration	N
Sample Interval	N

The well concentration database is:

Name	Type
ID	A10*
Sample Date	D*
Species	A15
Concentration	N

The field types are defined as follows:

A – specifies an alphanumeric field followed by its length

N – specifies a numeric field

D – specifies a date field

* denotes that the field is a key field - the structure must match in order to use it successfully in ARMOS

after the field denotes that it is a calculated field and you do not have to provide data in this field

Import file formats

Below are example database files for import for each database. These apply to space and comma delimited files. For the latter, the data must be surrounded by single quotes and separated only by a comma.

Locations

CW-111	2006.34	2541.98
CW-112	2004.79	2078.09
MW-01	2363.72	2181.46

Monitoring Wells

CW-111	6/18/85	165.10
CW-112	6/18/85	170.36
MW-01	2/28/92	178.67

Soil Boring

MW-01	1/01/1980	178
MW-02	1/01/1980	168
MW-03	1/01/1980	161

Fluid Levels

CW-111	03/16/92	165.10	59.92	59.92	0.00	105.18
CW-112	03/16/92	170.36	60.09	60.09	0.00	110.27
MW-01	03/16/92	178.67	73.95	73.95	0.00	104.72

Soil Concentrations

MW-01 18 TPH 1 2
MW-01 16 TPH 1 2
MW-01 15 BENZENE 1 2

Well Concentrations

MW-03 1/01/1980 BENZENE 2
MW-03 1/01/1980 XYLENE 2
MW-03 1/01/1980 BENZENE 2

2.3.3 Print

This selection allows you to print out all of the data in a given database file. When you select **Print,** a drop-down menu displays a list of all six database files. Select the one you want to print. A report consisting of all data in this file is sent to the printer. If you want to print a subset of data or data from more than one database file, use **Query** (Section 2.3.4 below). Make sure your printer has been configured correctly using **Setup / Printer.**

MW-05	286.34	233.56
MW-12	251.91	255.6
MW-23	202.192	243
MW-32	290.634	220.1

2.3.4 Query

Use this command to ask questions about and to extract selected data from an ARMOS project database. The **Query** command allows you to:

- Choose which database files to link and search.
- Choose which fields to display.
- Define selection criteria .
- Search for specific data.
- Select subsets of your data for further reduction, analysis, and reporting.
- Save and name Query results for later use.
- Discover trends and patterns in your data that can otherwise be difficult to see.

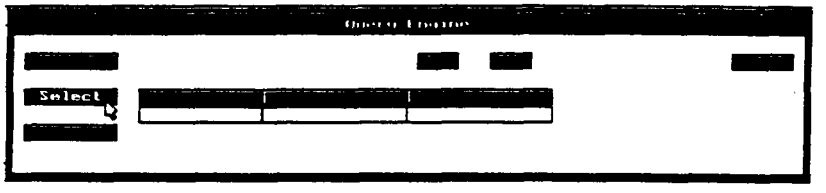
In addition, you can

- Overlay saved Query results on the workspace map (see Section 2.5.1).
- Graph Query results.
- Print Query results (data and graphs).
- Export to a file (see section 2.5.1- **Setting**).

Queries are composed by selecting database files and fields, and by entering selection criteria into a "Query form". When you select **Query** from the **Database** sub-menu, the Query Engine dialog box appears. The default Query fields are **ID**, **X Location**, and **Y Location** from the **Locations** database file (Figure 6). *If you are generating a **Query** results file for use as an overlay (Section 2.5.1 in this chapter), you must include, at a minimum, these three fields in your **Query**.*

*For overlays you must include the **ID** and the **X** and **Y Locations**.*

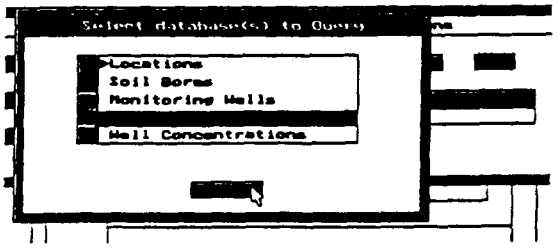
Figure 6



To select the database files you wish to query, click on **[Select]**. The Select Database(s) to Query dialog box appears. Use the mouse to select those database files you wish to query. When a file is selected, a black triangle appears to the left of the filename. Clicking on a filename toggles the selection status for that file. When making your selections, keep in mind that ARMOS will be using ID as the key field. In other words, only data with the same ID in *all*

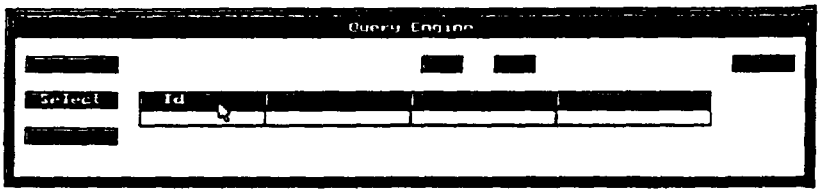
selected databases will appear in your **Query** results. In Figure 7 notice that **Locations** and **Fluid Levels** have been selected.

Figure 7



After selecting Fluid Levels the Query Engine dialog box appears with additional fields (Figure 8).

Figure 8



ID, **X Location**, and **Y Location** (the default **Locations** fields) have been joined by **Sample Date**. Here, **X Location** has scrolled off to the left and is no longer visible, and **Top of Casing** has scrolled into view from the right. Clicking on [>] displays Z_{ow}.

Following is a brief description of a query on Fluid Levels.

Clicking on the [**ID**] button (the shaded area) puts a check mark on that button. This tells you that the Query Engine will include this field in the **Query** search. This query is interested in [**X Location**], [**Y Location**] (ID, X Location and Y Location are required if you wish to overlay your results file on the workspace map later) [**Sample Date**], [**Top of Casing**] and [H_o]. This will select three fields from the **Locations** file (ID, X Location and Y Location) and three from **Fluid Levels** (Sample Date, Top of Casing, and H_o).

Selection criteria can be defined by using one or more of seven operators. These operators are as follows:

- AND logical and

- > greater than
- >= greater than or equal to
- < less than
- <= less than or equal to
- = equal to
- <> not equal to

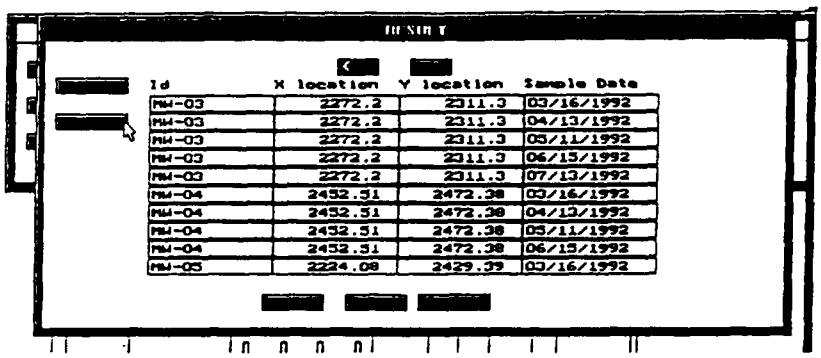
Only one instance of AND is allowed per criterion. The statement ">=5AND<10" is acceptable but ">=5AND<10AND>50AND <=75" is not. *Do not insert any spaces in your selection criteria except on either side of an AND statement.* AND can be used only in "number" and "date" type fields. The other six operators can be used in any type field.

In this query we are interested only in those samples for which well product thickness, H_o, is greater than zero, so directly below **[Ho]** we type **>0** and press **<Enter>**. Now we move the cursor to the white data entry space directly below **[Sample Date]**. We are interested only in data from wells sampled between January 1 and July 31, 1992, so we enter **>=01/01/92AND<=07/31/92.**

To perform the **Query** just defined, we click on **[Do Query]**. ARMOS searches the database for all sample records that match the selection criteria and displays the selected fields in a Result dialog box. The mouse cursor changes from an arrow to an hourglass for the duration of the search.

To view all of the results in the table, scroll left and right using the [>] and [<] buttons and up and down using **[Pg Up]** and **[Pg Dn]** (Figure 9).

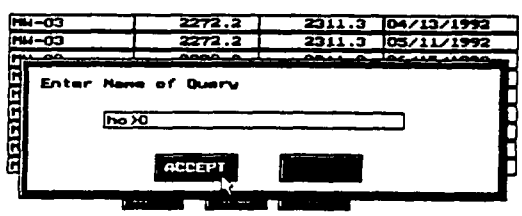
Figure 9



To print the results of your **Query**, select **[Print]** in the Query Result dialog box. Print operations, if desired, should be carried out before **[Save]** or **[Close]** are pressed since you will not be returned to the Result window once you have selected either.

To save the **Query** result to a file, click on **[Save]** (Figure 10). A dialog box appears with a field for naming your **Query**. **Saved Queries are saved only for the duration of the current session. ARMOS does not currently support saving Queries to disk for use in future sessions.**

Figure 10



If you decide not to save a **Query**, click on **[Close]** from the Result window or **[Cancel]** from the Query naming dialog box. The former takes you to the Query Engine set-up window, and the latter returns you to the Query Result dialog box.

2.3.5 Data import error messages and explanations

"Error.. Cannot open input file." This means the input file was not found. The file you want to import may be in another directory, or you may have miss-spelled the filename.

"DUP Ignored - Line %7i-" This means similar data exists in the data base– ARMOS will not overwrite data.

"The file format is incorrect and cannot be processed." This means the input file does not adhere to the format needed by the database for data you are trying to add.

"The format of line %d is incorrect" This means the particular line you entered could not be processed. For example you might have entered a date as 2-DEC-93, when ARMOS needs the format 12-2-93.

"Error in line number %d. Field should contain all digits." This means you have entered an invalid numeric format. For example entering "nine" instead of "9" would cause this message.

"Error in line number %d. Field should not contain any spaces." String fields should not contain spaces. For example "MW-01" is allowed, but "MW 01" is not.

"Error - type in database is undefined." If you see this message contact ES&T user support.

"Error in line number %d." There is an error in one of the lines of the file you are trying to import.

"Date should be of the form. MM/DD/YY[YY] or MM-DD-YY[YY]." This means you have entered a date separated by something other than slashes or dashes.

"General error code. Cannot process input file." This means the database is corrupt. You will need to restore the file from backup.

"Out of range error. Cannot process." This means the database is corrupt. You will need to restore the file from backup.

"Error, table write-protected." Either someone else is using this table or someone has made this table read only.

"General I/O error has occurred." This message means something is wrong with your computer.

"Specific I/O error: out of handles." Check to see if your "FILES=" line in your CONFIG.SYS is set to forty or greater; if not then change this. If this does not resolve the problem contact ES&T.

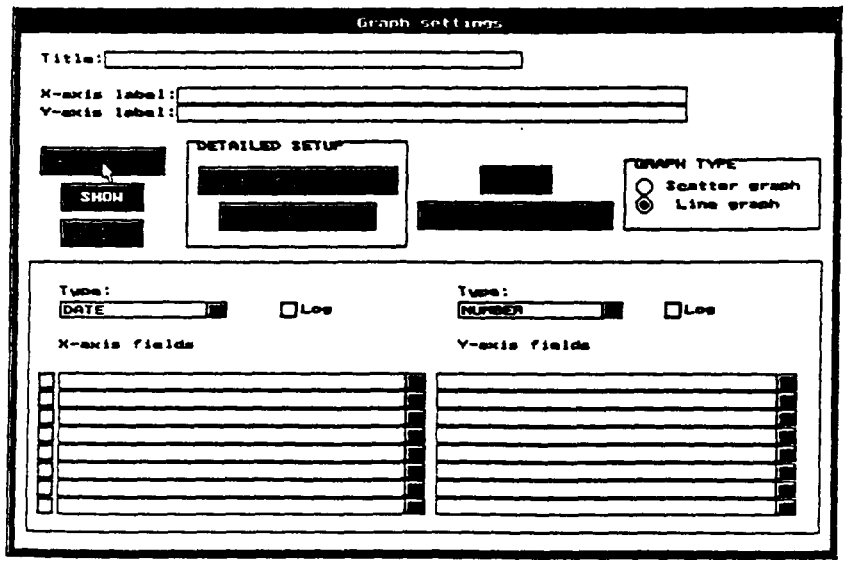
"Specific I/O error: access denied on open." Either someone else is using this table or someone has made this table read only.

"Specific I/O error: no more space to write." This means your hard disk is full. You can free up space, then retry.

2.4 Graph

The **Graph** command allows you to display and print a graph representing your Query Results as either a line graph or as a scatter plot graph. When you select **Graph** from the main menu, the Graph Settings dialog box appears.

Figure 11



To choose the **Query** results you will use for your graph, select **[Pick Query]** to display the Select Query to Graph list box. Select the desired **Query** results by clicking on the **Query** filename. Only one query file may be accessed for any one graph. When you have

made your selection, the list box closes automatically and returns you to the Graph Settings dialog box.

You do not need to enter a title, X-axis label, or Y-axis label to display the graph, but you may enter them if you wish. Choose the type of graph you would like by clicking on the hollow circle proceeding Scatter graph or Line graph. A solid circle inside of the hollow circle indicates your chosen graph type.

Click on [▽] to the right of the Type field above **X-axis fields**. A list with the selections DATE and NUMBER appears. Click on the data type you will be using for the X-axis data. Repeat the operation for the Y-axis data type.

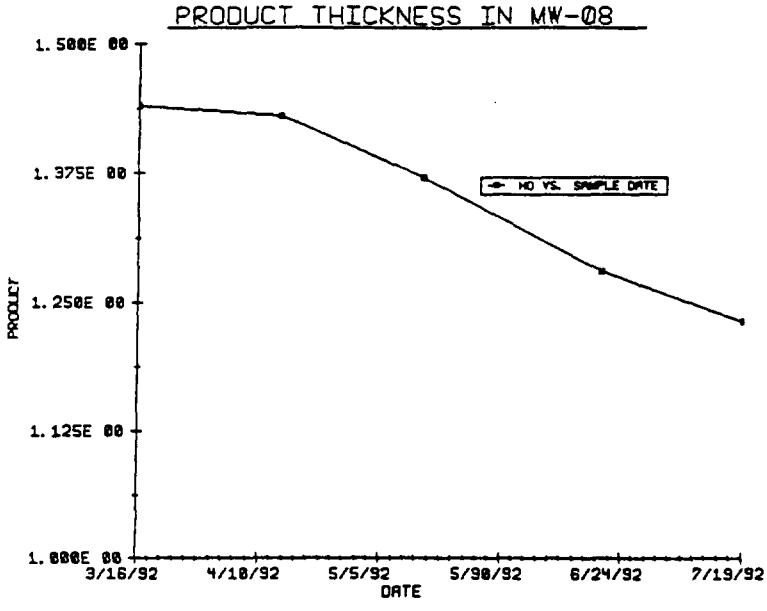
Next, you must select the data that you want displayed on each axis. Click on the [▽] button to the right of the first X-axis field to display a list of the available fields. Select the data you want to graph. Do the same with the first Y-axis field. If you would like a log-log or semi-log plot, click on the box(es) in front of **Log**. A boxed X indicates that the relevant axis will be logarithmic.

If you would like to plot more than one set of data from your **Query** file on the same graph, you may select additional X and Y fields by repeating this procedure in the second, third, fourth, etc. X-axis and Y-axis fields.

Next, click on the [☐] box to the left of the first X-axis field. Do the same for the second, third, fourth, etc. X-axis fields if you would like those data to show on your graph (Figure 12). A box with an X indicates data that will be shown; an empty box indicates data that will not appear on your graph. Now you are ready to view your graph. Click on **[Show]** to display the graph. You can also select to manually set the graphing parameters by toggling the **[Automatic/ Manual]** button and clicking on the **[Setup Details]** button. This presents you with a window in which you can set the minimum and

maximum values for the graph, the numeric format, width, precision and number of ticks (Figure 13).

Figure 12



To change the printer selection or destination click on the **[Printer Selection]** button.

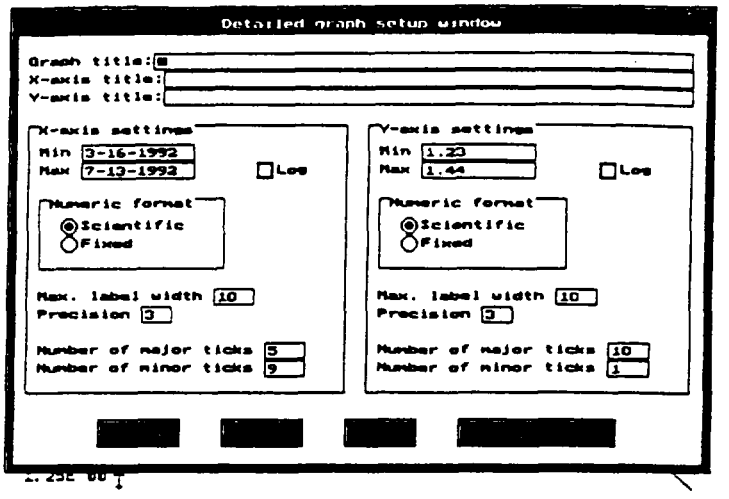
You may move the legend box by dragging it using the left mouse button. To return to the Graph Settings dialog box, either press the **<ESC>** key or click the right mouse button.

You may send the most recently generated graph to a file or printer (depending on your printer set-up, refer to Section 2.6) by clicking on **[Print]** in the Graph Settings dialog box. Note that graphs are not otherwise saved by ARMOS; you cannot retrieve graphs generated before the most recent graph. Note also that printing a graph(s) may take a (few) moment(s).

To exit the Graph Settings dialog box at any time, click on **[Cancel]**. ARMOS returns you to the main menu. To access the Setup

Details screen directly, press the left shift key and the left mouse button (Figure 13).

Figure 13



2.5 Map Operations

Selecting **Map** from the ARMOS main menu allows you to manipulate the workspace map for the current project. Operations that you can perform on the workspace map include: overlay tailoring (adding/ deleting overlays, changing overlay setup), redrawing the map, zooming in or out, setting the kriging domain, exporting the map, and printing the map including any visible overlays.

Before **Map** functions are described, the following three terms should be understood by the user.

Map Extents is the boundary of the map in the DXF file if you provide a DXF map file (it is optional). Note that map boundaries do not necessarily coincide with site boundaries. If you do not provide a DXF map file, the Map Extents defaults to a 10,000 foot by 10,000 foot area.

Data Domain defines the area from which data are extracted from the database for calculations. Only soil borings and monitoring wells within the Data Domain are used for database operations; all other soil borings and wells are excluded. Note that ARMOS requires a minimum of five data points within the Data Domain to

interpolate any field variable. By default, the Data Domain encompasses the same area as the Map Extents unless the user changes the coordinates of the Data Domain.

Kriging Domain defines the area for which ARMOS will perform interpolation from field data. If the Kriging Domain is larger than the Data Domain, results outside of the Data Domain will be extrapolated from data within the Data Domain. If the Kriging Domain is smaller than the Data Domain, no extrapolation of data is required (assuming data are available in the Data Domain outside the Kriging Domain). Obviously, better accuracy is possible if extrapolation is avoided. Note that the Kriging Domain is not used by the ARMOS Pre-/Post-processor.

2.5.1 Overlay

ARMOS can overlay layers of data, such as well locations or concentration gradients, onto the workspace map. Four default overlays are provided by ARMOS, and data files for additional overlays can be created using **Query** or the ARMOS post-processor.

Settings

Select **Map / Overlay** to access the overlay drop-down menu. If you click on **Setting,** ARMOS displays a list of all available overlays. (Note: Overlay data files generated by **Query** will not appear on this list until you use the **Add** function to add them to the list.) An overlay is displayed on the workspace map if there is a black triangle to the left of the overlay name.

Data Domain, Kriging Domain, Wells, and **Soil Borings** are default overlays and will automatically appear on your workspace map unless you turn them off, as described below.

Selecting **Data Domain** produces a CAD Drawing Settings dialog box with the following options.

Lower Left Corner	*X* - The X (Eastings) value for the left border of the Data Domain
	Y - The Y (Northings) value for the bottom border of the Data Domain

Upper Right Corner	*X* - The X (Eastings) value for the right border of the Data Domain *Y* - The Y (Northings) value for the top border of the Data Domain
Apparent Symbol Size	Adjusts the size of symbols used on the Data Domain to mark wells, borings, and pumps. The default size is determined as a percentage of the map extents. A larger symbol size may be necessary when the Data Domain is large, to enable you to see well, boring and pump locations.
Reset to Map Extents	Adjusts the Data Domain to include the same area as the Map Extents (refer to the definitions of Data Domain and Map Extents at the beginning of Section 2.4)
☐Automatic Redraw	When the box next to Automatic Redraw has an X, the workspace map is redrawn with active overlays each time a window is removed from the workspace. Since redrawing maps is time-consuming, you may want to turn off this feature by clicking in the box to remove the X. Clicking your right mouse button will redraw the workspace map.
☐Show Overlay	If the box in front of Show Overlay has an X, ARMOS overlays on the workspace map those drawings of physical features (tanks, buildings, etc.) appearing on your DXF map that are within the area defined as your Data Domain. If you do not have a DXF map file, the Show Overlay option for Data Domain turns the map on and off.
[Accept]	Saves the settings and returns you to the list of overlays.
[Cancel]	Exits to the list of overlays without saving any changes.

Selecting **Kriging Domain** produces a Kriging Domain Settings box with the following options:

Lower Left Corner	*X* - The X (Easting) value for the left border of the Kriging Domain.
	Y - The Y (Northing) value for the bottom border of the Kriging Domain.
Upper Right Corner	*X* - The X (Easting) value for the right border of the Kriging Domain.
	Y - The Y (Northing) value for the top border of the Kriging Domain.
[Reset Domain]	Resets the Kriging Domain to include the entire Data Domain. Any changes you have made to the Kriging Domain values are overwritten.
#Columns	The number of columns in your database mesh.
#Rows	The number of rows in your database mesh.
Delta X	Width of mesh columns (in map units).
Delta Y	Height of mesh rows (in map units).
☐Show Grid	When this box has an X, the mesh is displayed when ARMOS redraws the workspace map. If it does not have an X, the mesh is not displayed. Click in the box to change status.
☐Show Overlay	When the box in front of Show Overlay has an X, ARMOS draws a magenta box around the Kriging Domain when the workspace map is redrawn. If Show Grid (above) also has an X, ARMOS draws the mesh inside the Kriging Domain. Clicking on the box in front of Show Overlay toggles the status on and off.

[Accept]	Saves the settings and returns you to the list of overlays.
[Cancel]	Exits to the list of overlays without saving any changes.

Note that the Kriging Domain coordinates, number of mesh rows/columns, and the width of rows/columns are not independent of one another. Specifying two of these determines the third. ARMOS is designed to give priority to the number of mesh rows/columns, i.e., ARMOS will always adjust the width of rows/columns (ΔX, ΔY) rather than change the number of mesh rows/columns.

Selecting **Wells,** or **Soil Borings** produces a settings dialog box with only the Show Overlay option. If you would like wells, soil borings, or pump/recharge wells to appear on your workspace map, the box in front of Show Overlay should have an X. You may turn the X on or off by clicking the mouse cursor in the box. **[Accept]** takes you back to the list of overlays, saving any change in on/off status for the overlay. **[Cancel]** takes you to the list of overlays and ignores any changes you made for the overlay.

Settings are also available for user-generated overlays (generated from **Query** or **Model / Post-processor**).

Overlays generated by **Model / Post-processor** at each model output time include:

Z_{aw}	air-water table elevation (ft)
Z_{ow}	oil-water table elevation (ft)
Z_{ao}	air-oil table elevation (ft)
H_o	well product thickness (ft)
V_o	total oil volume per area (ft)
V_{of}	free oil volume per area (ft)
V_r	residual oil volume per area (ft)

For the selected printout locations, time series of the following variables can be plotted:

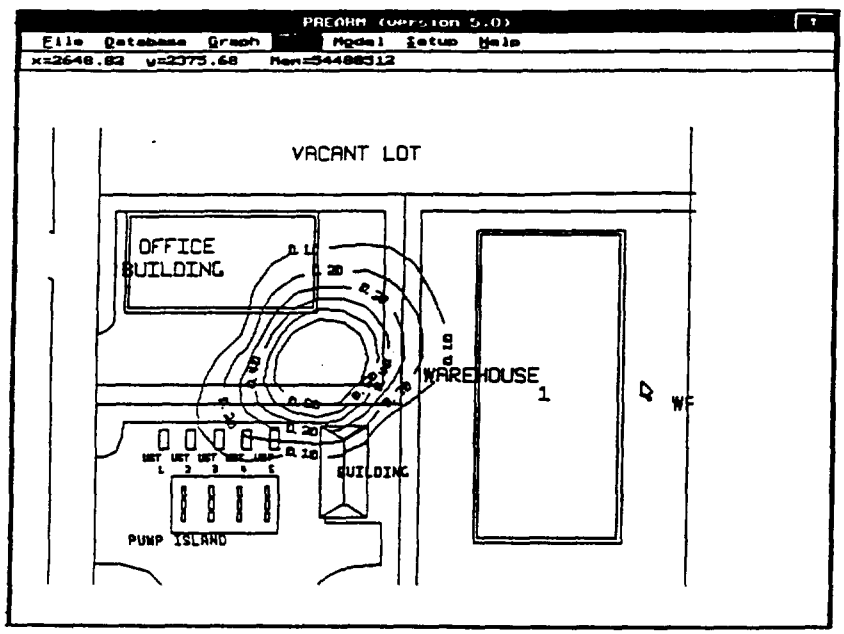
Z_{aw}	air-water table elevation (ft)
Z_{ao}	air-oil table elevation(ft)
H_o	well product thickness (ft)
V_o	total oil volume per area (ft)
V_{of}	free oil volume per area (ft)

For each recovery well the following can be plotted vs. time:

water pumping rate (ft^3/day)
oil pumping rate (ft^3/day)
cumulative water recovery (ft^3)
cumulative oil recovery (ft^3)

To view and/or adjust settings for a user-generated overlay, click on **Map / Overlay / Setting / [*Overlay name*]** to bring up an Overlay Settings dialog box (Figure 14).

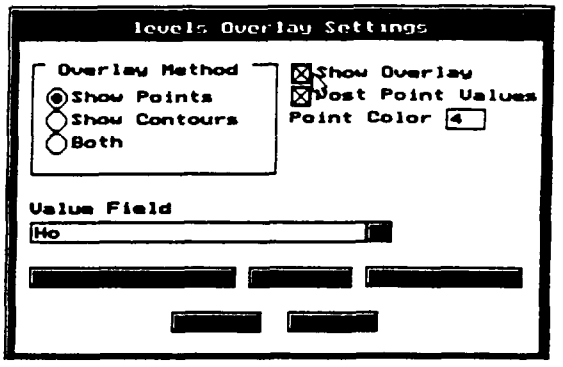
Figure 14



The Overlay Settings dialog box for **Query**-generated overlays contains *numerical* data in addition to ID, X Location, and Y Location. An abbreviated dialog box is displayed for **Query**-generated overlays containing only ID, X Location, and Y Location, or containing those three fields plus date(s), and/or species name(s). **Model**-generated overlay settings are restricted to those given in the Contour/Gradient Settings dialog box, plus an on/off switch. If you are interested only in **Model**-generated overlays, skip the next six paragraphs.

You may turn your **Query**-generated overlay on or off by clicking in the Show Overlay box. An X indicates that the overlay is displayed on your workspace map (Figure 15).

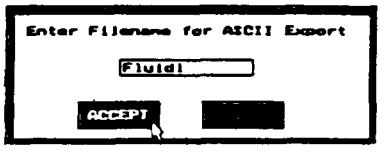
Figure 15



By clicking on the circles in the Overlay Method box, you may choose to overlay your data on the workspace map as points, you may have ARMOS interpolate to produce contours from the data, or you may show both points and contours. A solid bullet in any circle indicates the chosen overlay method. For **Query**-generated overlays containing only ID, X, and Y, or only ID, X, Y, Date(s), and/or Species name(s), there is no choice of Overlay Method; only points are possible.

You export your query data. Select **Map / Overlay / Setting**. In the Overlay Settings dialog box there is an **[Export]** button you can press. ARMOS asks you for an ASCII filename and the message "Export Complete" should show on your screen after you click on **[Accept]** (Figure 16).

Figure 16



Post Point Values gives you the option of displaying the point values for numerical data on your overlay (figure 15). An X in the box next to **Post Point Values** turns on this feature, and it can be toggled on or off by clicking on the box. This option is available only for **Query**-generated overlays containing numerical data in addition to ID, X and Y.

Point color determines the color used for points and contours. The following color codes are used by ARMOS:

0	Black
1	Blue
2	Green
3	Cyan
4	Red
5	Magenta
6	Brown
7	Light gray
8	Dark gray
9	Light blue
10	Light green
11	Light cyan
12	Light red
13	Light magenta
14	Yellow
15	White

Value field specifies the name of the parameter you wish to overlay (Figure 15). This option is available only for **Query**-generated overlays containing numerical data in addition to ID, X and Y. For a list of parameters available to you (determined by your Query Results file), click on the solid triangle on the right side of the Value Field box. Then click on the overlay parameter of interest to enter it into the Value Field box.

You may choose only one parameter to overlay at any one time. In other words, if you have two or more parameters-of-interest within a single **Query** file, you may view the corresponding overlays on the workspace map one at a time but cannot superimpose the overlays. Superimposing overlays is possible only if data are in separate **Query** files.

Choosing [**Krig Opts**] takes you to the Kriging Options dialog box. Your options for kriging are as follows:

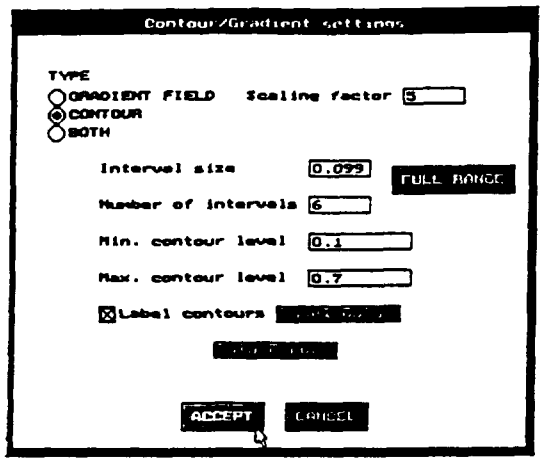
Use nearest ? data points	This value specifies the number of data points that will be used to interpolate at a node (if available). The default is 15.

Search radius	This is the distance from any node that ARMOS will search for data.
Minimum value	Set this to the minimum value you want ARMOS to krige (e.g., the lowest physically meaningful or measurable value).
Value to use if less than min.	Any kriged value on the grid less than "minimum value" well be set equal to this value.
☐ Set value to ? if no points in search radius	If this box is checked, any nodes with no data points within the search radius will be assigned the specified value.
☐ Krige log transform	If this box is checked, kriging will be performed on log-transformed data. Log-transformed kriging can be useful for interpolating data such as dissolved concentrations that are noisy and have a very wide range.Any non-positive data or kriging limits will be automatically set to 10% of the minimum positive value in the data set.

If you choose to display your data as contours or would like a gradient field, additional settings are available by clicking on [**Contour Options**] (Figure 15). The message "Kriging Column Value" is

briefly displayed, followed by a Contour Settings dialog box (Figure 17).

Figure 17



This dialog box is the only settings box displayed for **Model**-generated overlays.

Select your overlay method (contour or gradient field or both) by clicking on the corresponding circle under Type. A solid bullet in the circle indicates your choice. The remaining options are as follows:

Scaling factor	Controls the size of the arrows in a gradient field. As the scaling factor increases, arrow size increases.
Interval size	Determines the spacing between contour lines. Units correspond to those of your value field. A larger interval size decreases the number of contour lines.
Number of intervals	The number of desired contour lines.
Min. contour level	The smallest value that you would like to use as a contour level.
Max. contour level	The largest value that you would like to use as a contour level.
☐Label contours	An X in the box instructs ARMOS to label the contour lines with their

	corresponding values. Toggle on and off by clicking in the box.
☐Show overlay	This option appears in the **Contour Options** dialog box only for overlays generated by Model. The overlay appears on your workspace map if there is an X in the box in front of Show Overlay. Toggle on and off by clicking in the box. You can turn on or off overlays generated by **Query** from a previous settings dialog box.
[Full Range]	Click on this button to set the Min. and Max. contour levels to the minimum and maximum values in your value field, respectively.
[Accept]	Accepts your contour/gradient settings and returns you to the previous dialog box.
[Cancel]	Returns you to the previous dialog box without keeping any changes you made in the Contour/Gradient Settings dialog box.

Note that "Interval Size", "Number of Intervals", and "Min. and Max. Contour Levels" are not independent of one another. ARMOS uses the following rules to adjust these variables for **Query** generated contours:

If you change "Number of Intervals", ARMOS adjusts "Interval Size".

If you change "Min. Contour Level", ARMOS adjusts "Interval Size".

If you change "Max. Contour Level", ARMOS adjusts "Interval Size".

If you change "Interval Size", ARMOS adjusts "Number of Intervals".

After you have accepted or cancelled settings for your overlay, ARMOS returns you to the main menu.

For **Model / Post-processor** or **Pre-processor**, you can specify Interval Size, Max. Contour Level, and Min. Contour Level. The number of intervals is then internally calculated and not editable.

Add

The **Add** function adds **Query**-generated overlays to the list of overlays under the Setting menu selection above. Note that added overlays are not turned on from the Add function; you must return to Setting to turn overlays on or off.

To use the **Add** function, click on **Map / Overlay / Add** to bring up a list of **Query**-generated data files. These data files were created when you saved the results of a **Query** (as long as you included ID, X Location, and Y Location; see Section 2.3.4). Select the overlay data file(s) that you would like to add and click the mouse. You may add as many or as few of your Query-generated data files as you wish. The selected overlay file(s) will now appear in the list of overlays under the **Setting** menu selection.

Overlays generated by **Model / Post-processor** or **/ Pre-processor** are automatically added to the **Setting** list by ARMOS. You do not need to use the **Add** function for these overlays.

Delete

Selecting **Map / Overlay / Delete** removes overlays from the list of overlays under the **Setting** menu selection. All default overlays (those that are not generated by using **Query** or **Model / Post-processor** or **/ Pre-processor**) are protected from deletion.

2.5.2 Redraw

Redrawing the workspace map can be computationally intensive. When overlaying monitoring wells or soil bores, for example, ARMOS might have to sift through hundreds or thousands of data points to render an updated workspace map. If the map is redrawn each time a window is added and removed from the workspace, ARMOS spends more time drawing the map than doing useful work for you. On the other hand, not redrawing the map each time a window is removed from the workspace can result in a map pocked with holes.

ARMOS is preset with automatic redraw turned off. To turn on the automatic redraw feature, select **Map / Overlay / Setting / Data Domain** and click on the boxed X in front of **Automatic Redraw**. When the X is removed from the box, the automatic redraw feature is turned off. You may turn it back on if you wish by clicking again on the same box.

With the automatic redraw feature turned off, you may still periodically update the workspace map on your screen by selecting **Map** from the main menu and then **Redraw** from the drop-down menu, or simply click on your right mouse button. Redraw is also available from the **Map / Overlay** drop-down menu. ARMOS redraws the map including any active overlays.

2.5.3 Zoom

You may often find a need to examine the workspace map in greater detail, such as when you want to get detailed information on a specific area or when a plume occupies only a small area in relation to the full workspace map. Selecting **Map / Zoom** displays another drop-down menu with the choices **Zoom Area** and **Zoom Reset**.

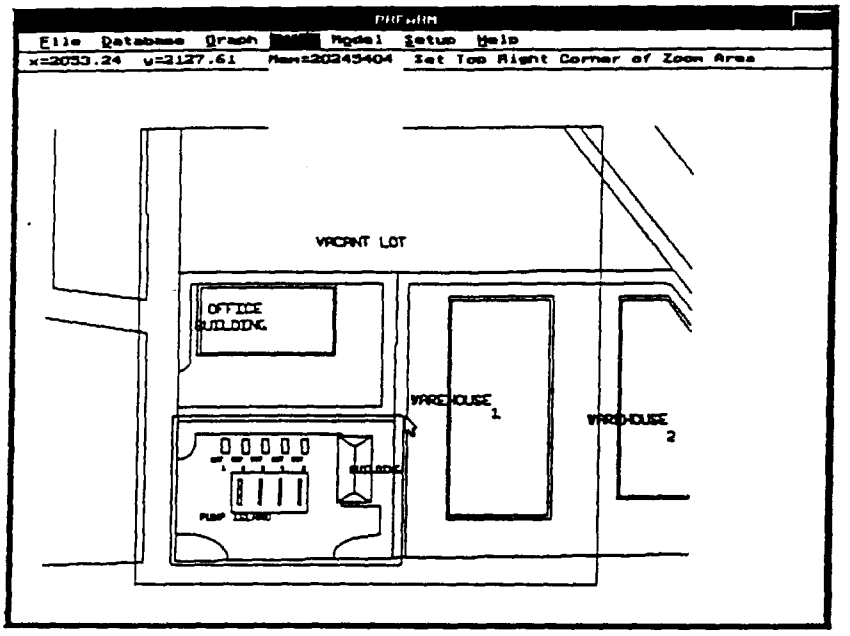
Zoom Area

To zoom in on an area, select the **Zoom Area** function. The Zoom drop-down menu closes and the message "Set Bottom Left Corner of Zoom Area" is displayed on the status line.

Position the mouse pointer on the lower left corner of the area you want to zoom and click the left mouse button. Notice that the message on the status line has changed to "Set Top Right Corner of Zoom Area". Now when you move the mouse up and to the right,

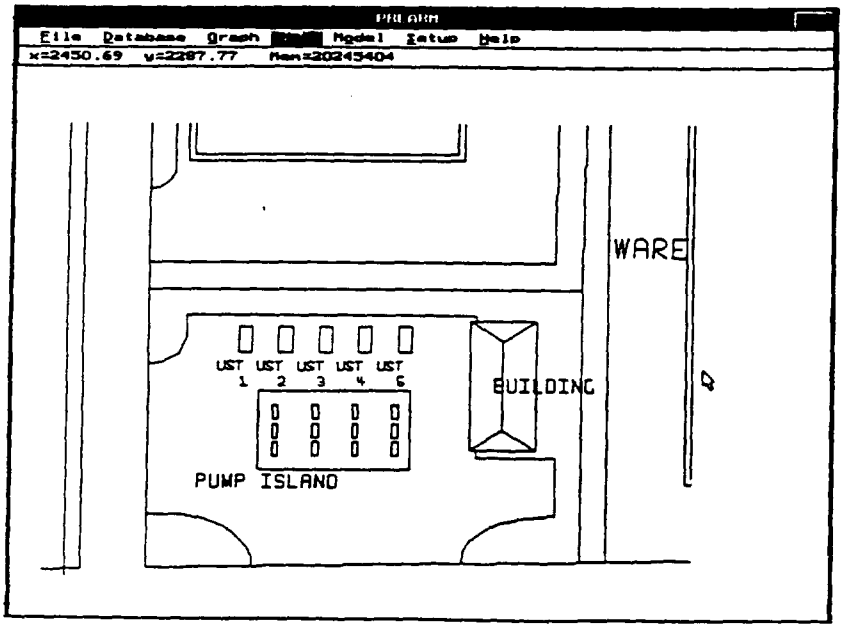
an adjustable box appears on the screen to assist you in defining the zoom area (Figure 18).

Figure 18



Adjust the box to the desired dimensions and click the left mouse button. ARMOS enlarges and redraws the selected area of your map to fill the window (Figure 19).

Figure 19



ARMOS maintains the aspect ratio (the ratio of width to height) of the original map. This means that if you select a relatively square zoom box, the full height of your selection is zoomed. The zoom box is adjusted to display enough width to fill the screen. If you select a short, wide zoom box, the width of the zoom box is fitted to the full screen width and the height adjusted to fill the screen.

Zoom Out

Zoom Out returns you to your previous zoom screen.

Zoom Reset

When you select **Map / Zoom / Zoom Reset**, ARMOS redraws the workspace map and any active overlays to their original size.

2.5.4 Pan

Pan allows you to move around in the map area. This feature is most useful when you are zoomed on a specific part of the map and want to look at an area just off screen, but do not want to reset zoom then re-zoom on the desired section. Select **Map / Pan**, then click on a point of the screen you want to pan toward. Move the cursor to the area on screen where you want the first point to *arrive*, then click the left mouse button.

2.5.5 Kriging Domain

Kriging Domain defines the area for which ARMOS will perform interpolation, i.e. the Kriging Domain.

Domain Set

To define the Kriging Domain, choose **Map / Domain** from the main menu. Another drop-down menu appears with the choices **Domain Set**, **Domain Reset**, and **Settings**. Select **Domain Set**. Note that the message "Set Bottom Left Corner of Domain" appears on the status line.

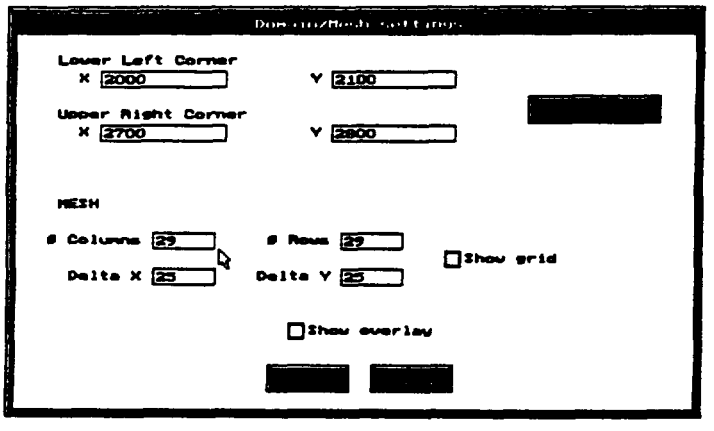
Position the mouse pointer on the lower left corner of the new domain and click the left mouse button. Notice that the message on the status line has changed to "Set Top Right Corner of Domain". Now when you move the mouse up and to the right, an adjustable box appears on the screen to assist you in defining the Kriging Domain.

Adjust the box to the desired Kriging Domain dimensions and click the left mouse button again. ARMOS redraws the workspace map and all active overlays. If the Kriging Domain overlay is active, the new Domain is displayed.

Use **Map / Domain / Settings** if you want to specify coordinates of the Kriging Domain or change the grid spacing for calculations.

Select **Map / Domain / Settings** from the main menu. A dialog box appears (Figure 20). A description of each option available in the dialog box is given below. For the Data Domain Settings dialog box see Section 2.5.1.

Figure 20



Lower Left Corner	*X* - The X (Eastings) value for the left border of the Kriging Domain
	Y - The Y (Northings) value for the bottom border of the Kriging Domain
Upper Right Corner	*X* - The X (Eastings) value for the right border of the Kriging Domain
	Y - The Y (Northings) value for the top border of the Kriging Domain

[Reset Domain]	Resets the Kriging Domain to include the full workspace map. Overwrites any changes you have made to the Domain values.
#Columns	The number of columns in your mesh.
#Rows	The number of rows in your mesh.
Delta X	Width of mesh columns (in drawing units).
Delta Y	Height of mesh rows (in drawing units).
☐Show Grid	When this box has an X, the mesh is displayed when ARMOS redraws the workspace map, provided that Show Overlay (below) is turned on. If it does not have an X, the mesh is not displayed. Click in the box to change status.
☐Show Overlay	When the box in front of Show Overlay has an X, ARMOS draws a magenta box around the Kriging Domain when the workspace map is redrawn. If Show Grid (above) also has an X, ARMOS draws the mesh inside the Kriging Domain. Clicking on the box in front of Show Overlay toggles the status on and off.
[Accept]	Saves the settings and returns you to the main menu.
[Cancel]	Exits to the main menu without saving any changes.

Note that the Kriging Domain coordinates, number of mesh rows/columns and the width of rows/columns, are not independent of one another. Specifying two of these determines the third. ARMOS is designed to give priority to the number of mesh rows/columns, i.e., ARMOS always adjusts the Kriging Domain coordinates or the width of rows/columns rather than changing the number of mesh rows/columns.

2.5.6 DXF Export

DXF Export allows you to send your entire map (as defined by Map Extents; see definitions in Section 2.5.1) plus all overlays, regardless of whether or not they are turned on, to a DXF file. The file can then be used in programs such as AutoCAD.

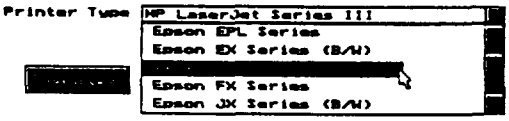
To Export your ARMOS map, click on **Map / DXF Export**. A dialog box appears asking you to name the DXF file you are creating. Enter a name and click on **[Accept]** to send your map to the file or **[Cancel]** to abort the operation. In either case, ARMOS returns you to the main menu.

2.5.7 Print

Clicking on **Print** sends a bitmap of the workspace map and active overlays *as displayed* to the printer. Make sure your printer has been configured correctly using **Setup/Printers**. Printing graphics can be time consuming, so please be patient.

2.6 Printer Setup

2.6.1 Selecting an output device



In order to produce any hardcopy output, or to send information to a file, you must first select the printing device. You can do this in ARMOS by selecting **Setup** from the main menu and then **Printer** from the drop-down menu. A window appears displaying the current printer choice and the port to which you are printing.

Your choice of Port tells ARMOS where to send the information you want printed, and Printer Type determines which printer control characters are included with your information. If you want to send information to a file with the intention of printing it later on a known type of printer, select your printer type from the list and choose FILE for your Port selection. If you do not know what type of printer you will use, or do not intend to send the data to a printer, select FILE for your Printer Type and Port. If you want to send the information immediately to a printer, select your printer type from the list and choose the appropriate port (LPT1, LPT2, COM1, or COM2).

To select the type of printer you want to use, click the mouse on the solid triangle to the right of the Printer Type field. This opens a listing of the supported printers. To choose a printer from this list, use the scroll bar to move through the list, and then click the mouse on the name of the desired printer.

To select the port to which you will print, click the mouse on the button next to your choice of the ports listed in the PORT box. ARMOS currently supports printing to the standard printer ports **LPT1** and **LPT2**, the two standard serial ports **COM1** and **COM2**, and to **FILE**. If you select **FILE**, ARMOS does not prompt you for a file name until you print.

Clicking on **[Graphics Options]** produces a window that allows you to set the actual plot width and height, plot orientation, and resolution.

Click on **[OK]** to accept the printer and port selections, or **[Cancel]** to keep your previous selections. Either returns you to the main menu.

2.6.2 Producing graphics output

Currently ARMOS supports three types of graphical printouts: a full screen dump, a printout of only the current map display, and a graph print.

To produce a screen dump, make sure that you have the proper printer type and port selected, configure the screen display as desired and press **<CTRL> P**. The mouse cursor disappears while the screen is captured and printed. This method will print the entire screen including the window, menu and border.

To print only the workspace map with any current overlays, select **Map** from the ARMOS main menu and **Print** from the drop-down menu. When you click the mouse on **Print**, the mouse cursor disappears while the output is routed to the selected output device in the format of the currently selected printer.

To print a graph, select **Graph / [Print]** after you have viewed the graph.

2.6.3 Producing text output

You can print most of ARMOS's databases. To do this, choose **Database** from the ARMOS main menu and then **Print** from the drop-down menu. A second drop-down menu listing the databases which you may print appears.

Choose the database you wish to print by positioning the mouse cursor on it and clicking the mouse. The printout is routed to the output device specified in **Setup / Printer**.

Note that ARMOS prints the data you select for ALL monitoring wells, or ALL soil bores, etc. You may not specify only one monitoring well, soil bore, etc., since ARMOS does not print parts of files.

If you want to print selected data, use **Database / Query** to generate the desired data subset, then select **[Print]** from the **Query** results dialog box.

3. ARMOS Pre-processor and Post-processor

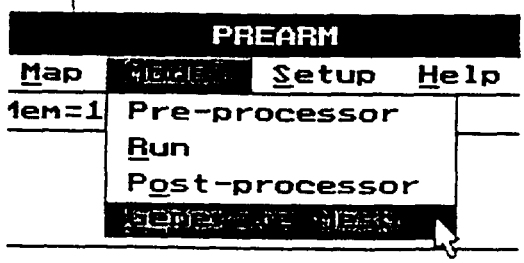
3.1 Overview

ARMOS consists of two programs: the Pre-/Post-processor called PreArm and the main finite element program called RunArm. The main program reads input data files prepared by PreArm and creates output files that are read back into the PreArm Post-processor. PreArm provides a graphical user interface with the capability to access a database and to display DXF drawings on screen. The graphical interface allows you set up simulations quickly and accurately, without worrying about file formats and input structure. The post-processor reads the main output file from the numerical model and processes the results so that you can view, edit and print time series and contour plots of the model output.

3.2 Mesh Generator

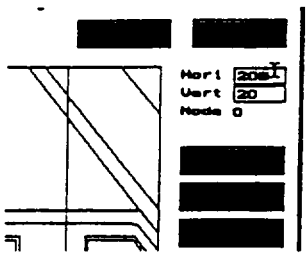
3.2.1 Generate Mesh

This facility allows you to generate the finite element mesh used to do numerical computations. Both horizontal and vertical lines of the mesh as seen in plain view on the screen (i.e., north and south on the map), can be added, moved, and removed using the PreArm Mesh Generator.



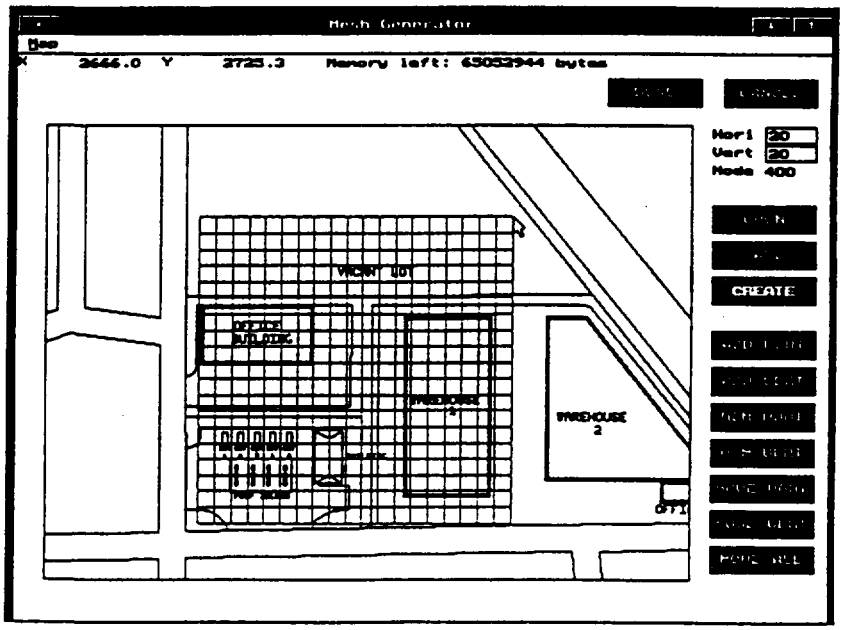
The first step in creating a mesh is to specify the base number of horizontal and vertical lines in the mesh to be generated. This is specified in the two input boxes in the upper right hand corner of the edit window, labelled "**hori**" and "**vert**" (Figure 1). Values for these two parameters can be entered by placing the cursor in the box and clicking the left mouse button. The value listed beside "**node**" is the total number of nodes that the specified number of horizontal and vertical lines will generate.

Figure 1



After the number of horizontal and vertical lines have been specified, the second step is to define the rectangular boundary for the finite element mesh. Click on the **[Create]** button and then define the rectangle as you would a zoom box, clicking first on the lower left corner of the domain, then dragging the top left corner of the domain box to its desired location. This will create the base structure for the mesh.

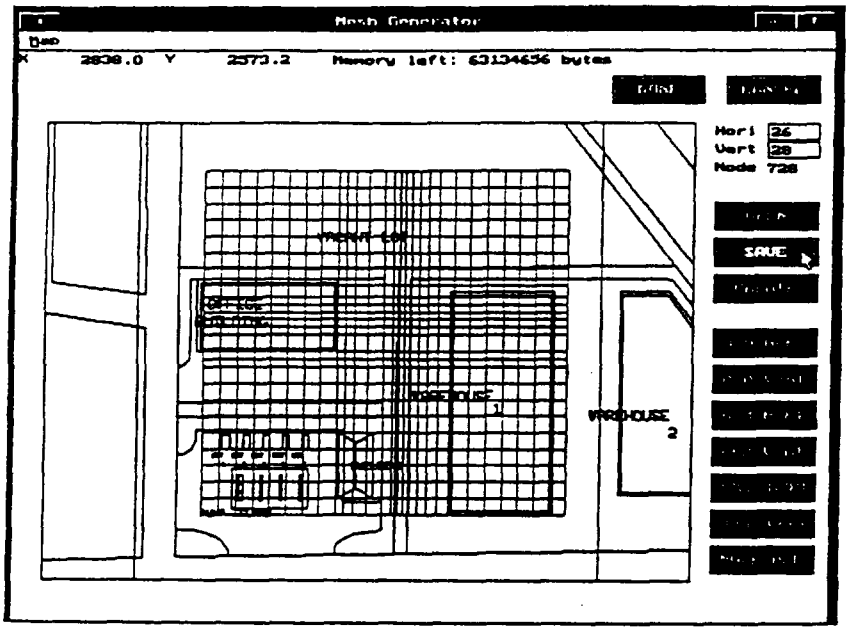
Figure 2



The **[Open]** button brings up the file selector box, and prompts you for the name of a previously created mesh file. This File may be revised and manipulated by the mesh generator. If the mesh for a previously generated data set is modified and saved as the same name, that data set will need to be revised because the spatial data code will no longer correspond to the menu locations.

ARMOS currently only provides a mesh generator to create regular rectangular meshes, although the numerical model is capable of using user-generated irregular meshes with any combination of linear quadrilateral or triangular elements. The format for mesh files is given in Appendix A for users who may wish to create irregular meshes external to the ARMOS Pre-processor.

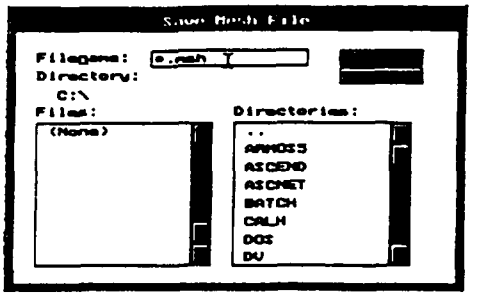
Figure 3



The [**Add Hori**] and [**Add Vert**] buttons allow you to insert additional lines in the respective directions. This allows the use of more nodes in areas requiring finer resolution, and for horizontal and vertical spacings to be nonuniform. The [**Move Hori**] and [**Move Vert**] buttons facilitate the movement of horizontal and vertical mesh lines. The spacing between adjacent grid lines should generally not differ by more than a factor of 2. A representative grid is shown in Figure 2.

The [**Move All**] button allows the entire mesh to be moved relative to the coordinate system. The [**Done**] button prompts as to whether you want to save your changes in the mesh if the mesh has changed. Answering yes brings up the save mesh file menu box, and prompts you for a *.msh file name. The [**Save**] button also brings up the file selector box, allowing you to specify which directory and file name the mesh file is saved under (Figure 4). Answering no returns you to the main menu, as does the [**Cancel**] button.

Figure 4



3.3 Creating Input Files with the Pre-processor

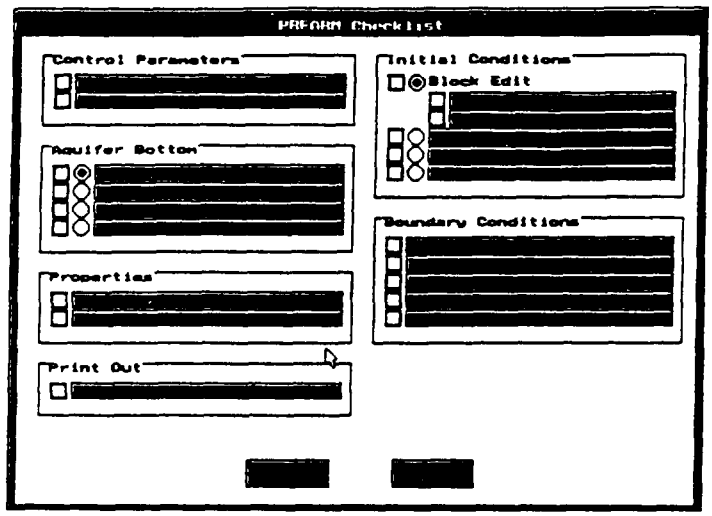
To use the Pre-processor for ARMOS, select **Model / Pre-processor** from the main menu. Select **New** to open a new file, or **Open** to return to a previous file. When you select **New**, PreArm places you in the file selection dialog box. You can change directories here–for example, if you want your new datafile to be in a directory you have created. After you enter a new file name and press **[Accept]** the file selection dialog box will ask you for a mesh file name. This mesh file contains coordinates of nodes and element connectivity for the finite element mesh, previously created by selecting the **Model / Generate Mesh** option from the main menu. Choose the mesh you want to use for your current datafile.

If you select **Open** under **Pre-processor**, the file selection dialog box will prompt you to choose a previously saved datafile.

The Pre-processor dialog box (Figure 5) is a checklist with the following main sections:

Control Parameters
Aquifer Bottom Elevation
Soil and Fluid Properties
Print Out (Locations)
Initial Conditions
Boundary Conditions

Figure 5



Although it isn't strictly necessary, we recommend setting up a new datafile by following the checklist in the order given. Many of the checklist items involve specifying spatially variable parameters (soil types, boundary conditions, wells, etc.), which are defined on nodes in the mesh.

3.4 Control Parameters

3.4.1 Model flags

Model flags are used to set up control variables for program execution.

Execution control

Under execution control, the following options are available (Figure 6):

Solve for initial conditions only: ARMOS will only compute initial conditions. Input data and initial conditions will be written to the main output file. Whenever running a new problem, or when making significant changes in an old file, this option should be used to verify data before running the problem.

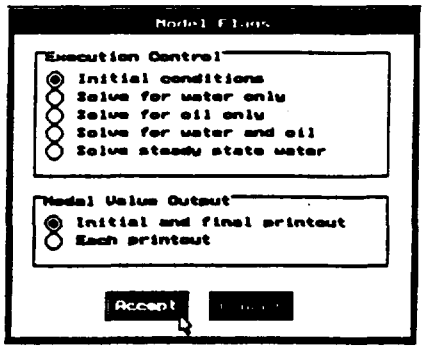
Solve for water only: the program will solve for transient water flow. Oil thickness will be internally set to zero.

Solve for oil only: the program will solve for transient oil flow with the air-water table internally set at the initial condition.

Solve for water and oil: the program will solve for coupled transient water and oil flow.

Solve for steady-state water only: the program will solve for steady-state water flow only.

Figure 6



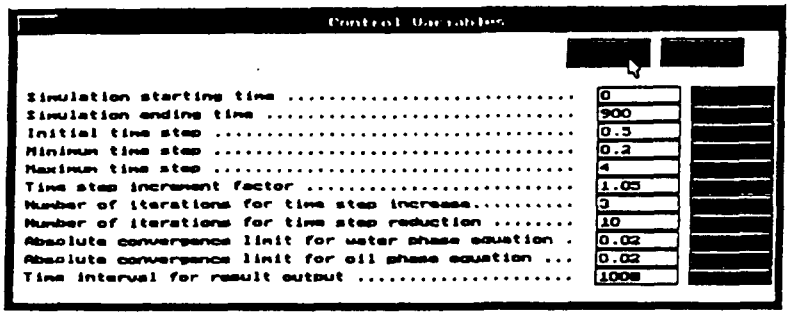
Nodal value output

This switch controls whether nodal values are printed at all printout times or only at initial and final time steps. Nodal values are needed for contour plots. If this option is on and a small printout time interval is used for a long simulation, the size of the output file will be large.

3.4.2 Model times

Starting and ending simulation time, parameters for setting up time steps and printouts are explained in the following sections (see Figure 7). All simulations will start with the initial time-step. The program will increase the time-step using a time-step incremental factor if the solution converges within a specified number of iterations. It will not allow a time-step larger than the maximum time-step.

Figure 7



Time units of days must be used to maintain consistency throughout the dataset.

Starting time: Starting time of the simulation is usually zero, except for a restart problem. If the problem is a restart, starting time will typically be assigned the time corresponding to the end of the previous run.

Ending time: When the current time is equal to or greater than the ending time for transient flow simulations, execution terminates.

Initial time-step: The initial time-step size for transient flow problems typically ranges from 0.001 to 0.1 days, depending on soil properties, mesh size and severity of imposed boundary conditions. A smaller initial time-step is usually needed to simulate pump start up, and for more permeable soils.

Minimum time-step: If ARMOS attempts to cut the time-step below the minimum time-step due to nonconvergence, the program will stop execution. It is advisable to make the minimum time-step larger or equal to the initial time-step so that if the solution does not converge with the initial time-step, the program will stop. Then you can adjust the time-step manually. If boundary conditions change abruptly later in the simulation, you should set the minimum time-step to be smaller than the initial time-step.

Maximum time-step: The maximum time-step can be from 0.5 to 5.0 days or greater, depending on the soil properties, mesh size and severity of imposed boundary conditions.

Time-step increment factor: If the number of iterations is smaller than the number of iterations for time-step increase, the next time-step is increased by the specified time increment factor. Recommended values are from 1.03 to 1.1.

Number of iterations for time-step increase: If the number of iterations for solution to converge is less than or equal to the specified number of iterations, the program will automatically increase the time-step size by the time-step increment factor. Recommended values are from 3 to 5.

Number of iterations for time-step reduction: If the number of iterations for solution to converge exceeds the specified number of iterations, the program will cut the time-step size by a factor of 2 and re-solve for the time step using a smaller step. Recommended values are from 9 to 12.

Absolute convergence limit for water phase equation: Convergence for the water flow equation requires that the change in Z_{aw} since the last iteration is less than the convergence limit for all nodes. Recommended values are 0.01 to 0.05 feet.

Absolute convergence limit for oil phase equation: Convergence for the oil flow equation requires that the change in Z_{ao} since the last iteration is less than the convergence limit for all nodes. Recommended values are 0.01 to 0.05 feet.

Time interval for results printouts: Specifies the time period between printouts of model results. Output files can become very large if the print interval is small.

Length units for all model input and output are in feet

3.5 Aquifer Bottom Elevation

These are four options available for entering aquifer bottom elevations. Use the "block edit" option if nodal values are known. Use "measurement points" to interpolate aquifer bottom elevations from known data. When the "constant thickness" option is used, aquifer bottom elevations are computed by subtracting the specified thickness from the initial air-water table elevations. Use the "constant elevation" option to set aquifer bottom elevation for all nodes to a constant value.

3.5.1 Block edit

Invoking the Block Edit option brings you to the Block Edit window for specifying aquifer bottom elevations (Figure 8). Click on **[Define]**. Define a zone by clicking on points that will circumscribe the area to be assigned a like value. You must next enter the corresponding elevation value and click on accept to assign that value to all nodes inside the zone. A single node may also be changed by clicking on that node, entering a value for the elevation, then clicking on **[Accept]**. After you are finished editing bottom elevations, click on **[Done]** to exit and save your work.

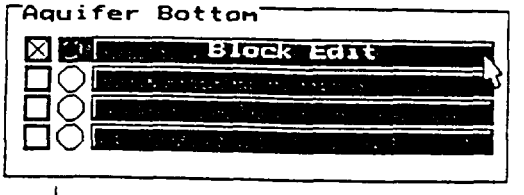
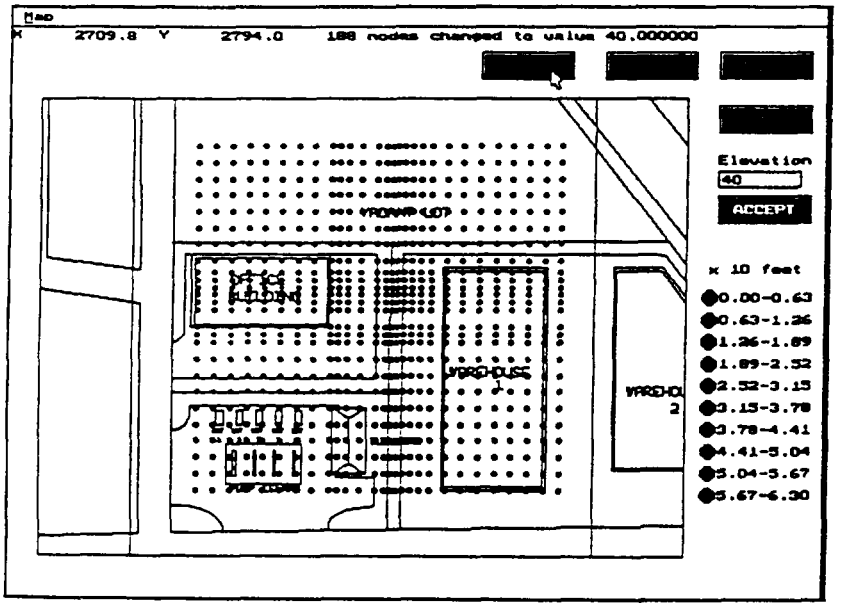


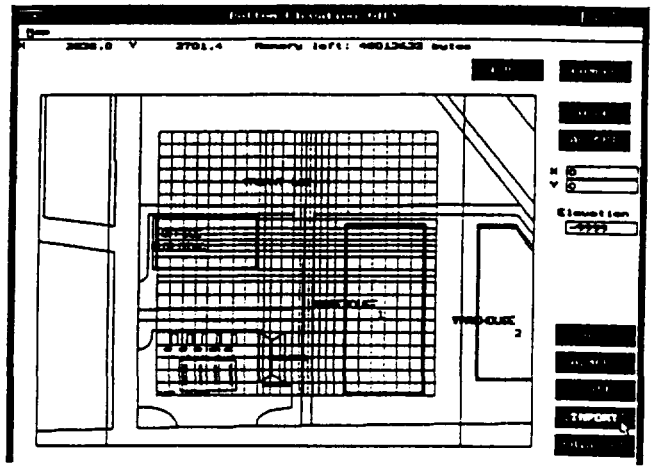
Figure 8



3.5.2 Measurement points

This option is used to interpolate nodal values of aquifer bottom elevations from measurements (Figure 9). If you want to enter a measurement point, first click on **[Add]** and move the mouse to the desired location and click the left mouse button. Enter the measured bottom elevation, then click on **[Accept]**. Use **[Remove]** and/or **[Edit]** to delete and/or edit a current measurement point. You can also **[Import]** from a datafile (*.ele format) and set **[Kriging Option]** (see Chapter 2 for an explanation of kriging options). After you are finished entering measurement points, click on **[Done]** to exit and save your work.

Figure 9



3.5.3 Constant elevation

When this option is used, aquifer bottom elevation for all nodes is set to a constant value.

3.5.4 Constant thickness

When this option is used, aquifer bottom elevation is computed by subtracting the constant thickness from the initial air-water table elevation (Z_{aw}).

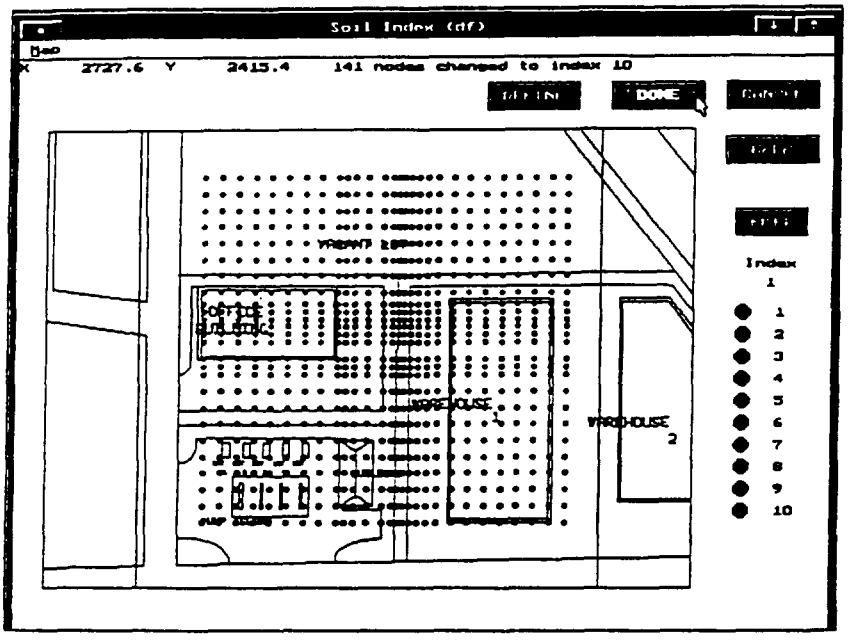
3.6 Soil and Fluid Properties

PreArm provides for the entry and estimation of soil and fluid properties used in various calculations.

3.6.1 Soil properties

Soil capillary properties are defined by van Genuchten (VG) model parameters. ARMOS allows up to 10 different soil types within the model domain (see Figure 10).

Figure 10



To define a soil type zone and enter VG parameters, first click on **[Define]** and use the left mouse button to define an area on the mesh by drawing a border around the desired area. The last point of the bounded area must coincide with the first point. Click on a desired soil index button to set the soil type index, and click on **[Edit]** to enter VG parameters for the soil type (Figure 11).

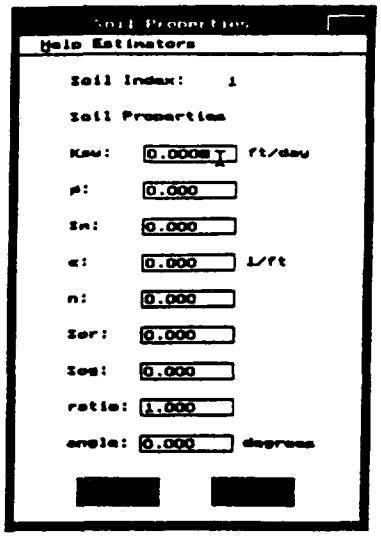
You may enter known parameter values and/or you may select **Estimators** from the menu. Section 3.6.2 describes how to use the Estimators.

You may also choose **Help** from the menu to display acceptable parameter ranges (Figure 11). Note that the initial soil parameters for a new project will all be set to zero, an invalid value for all of the parameters.

3.6.2 Entering known soil parameter values

To input known parameter values, place the mouse cursor on the appropriate field and press the left mouse button. The data entry cursor appears. Enter the desired value using the keyboard. You can use the left and right arrow keys to move around within the data entry field, and **<Tab>**, **<Shift-Tab>** and the up and down arrow keys to move from field to field (Figure 11).

Figure 11



K_{xw} is the horizontal saturated hydraulic conductivity of the aquifer in feet per day. If vertical variability occurs, the conductivity in the upper few feet of the aquifer is most relevant to model oil flow. The allowed range is $0.0001 < K_{xw} < 1{,}000$ feet per day.

ϕ is the total porosity of the soil in the vicinity of the capillary fringe expressed as a fraction. The allowed range is $0.1 < \phi < 0.7$.

S_m is the irreducible water saturation of the soil at field capacity -- that is, after water drains under the influence of gravity. Values are expressed as a fraction. The allowed range is $0.05 < S_m < 0.95$.

α is a parameter in the van Genuchten capillary pressure model that is related to the mean pore size of the soil. Capillary fringe thickness varies inversely with the parameter. The allowed range is $0.01 < \alpha < 100$ 1/feet.

n is a dimensionless parameter in the van Genuchten capillary pressure model related to the range of the pore size distribution. Smaller values correspond to broader pore size distributions. The allowed range is $1.1 < n < 10$.

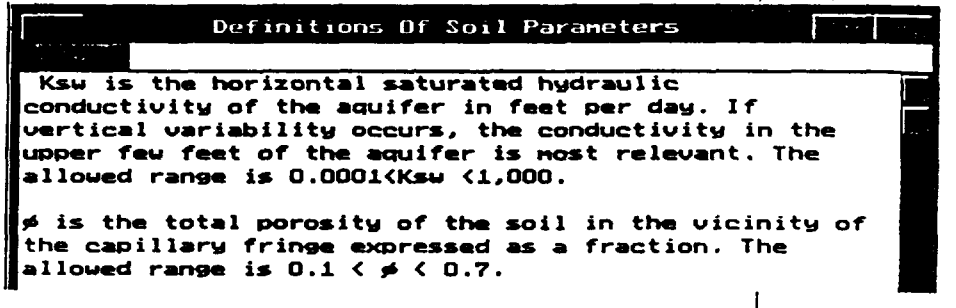
S_{or} is the maximum residual oil saturation in the saturated zone after water imbibition displaces oil from an initially high oil saturated zone (i.e. oil displaced by water). Values are expressed as a fraction. The allowed range is $0 < S_{or} < 0.5$. Residual saturations are also restricted such that $S_m + S_{og} + S_{or} < 1$.

S_{og} is the maximum residual oil saturation in the unsaturated zone after drainage of oil from an initially high oil saturated zone (i.e. oil displaced by air). Values are expressed as a fraction. The allowed range is $0 < S_{og} < 0.4$, subject also to the constraint that $S_m+S_{og}+S_{or} < 1$.

Anisotropy angle of conductivity is defined as the angle in degrees clockwise between the Y-direction (vertical on screen) and the maximum principle direction of the conductivity tensor.

Anisotropy ratio is the quotient of maximum principle conductivity by minimum principle conductivity. Set anisotropy ratio to 1 if soil properties are isotropic.

Selecting another field in the window will prompt PreArm to validate the contents of the previous field. If the value is valid, the cursor moves to the next field. If the value is invalid, an error message appears which must be acknowledged by selecting either the **[Cancel]** button or the **[Help]** button. The **[Help]** button opens a Help



window to provide additional information on selecting the soil parameter. Once the error message has been acknowledged (by selecting **[Cancel]**), or the Help window closed and followed by acknowledgment of the warning (by selecting **[Cancel]**), input may continue. You are not allowed to **[Accept]** the data until all values are valid. A list of valid ranges is available by selecting Help from the Soil Parameters dialog window menu.

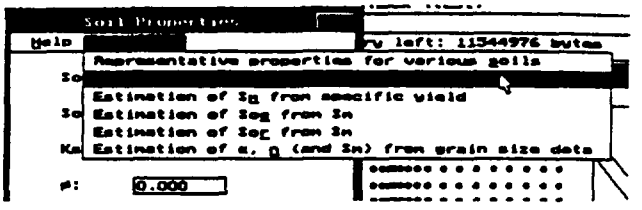
When you have finished entering the VG soil parameters, select **[Accept]** to use these data in any further calculations, or **[Cancel]** to revert to the previous values. Selecting **[Cancel]** returns you to the main menu and any changes you have made are not saved. If you choose **[Accept]**, PreArm returns you to the main menu, after saving your changes.

3.6.3 Estimating Soil Parameter Values

If you are unsure of a soil parameter value, or you do not understand what data is being requested, PreArm can assist you.

Choosing **Estimators** produces a drop-down menu of property estimators that may be used to compute various soil parameters (Figure 12).

Figure 12



Selecting the first choice in the estimator drop-down menu brings up a list box of representative soil types and their corresponding parameter values . The scroll bar on the left of the display allows you to navigate the list.

To choose one of the items in the list, place the mouse cursor on it and click the left mouse button. This closes the window and enters the values in the corresponding column of the Soil Properties window.

To exit this window without making a selection, click on **[Cancel]**.

If you do not wish to select a soil from the list of representative soils, an alternative is to estimate individual soil parameters by giving PreArm certain data from which soil parameters may be estimated.

Your choice of estimators supported by PreArm is as follows:

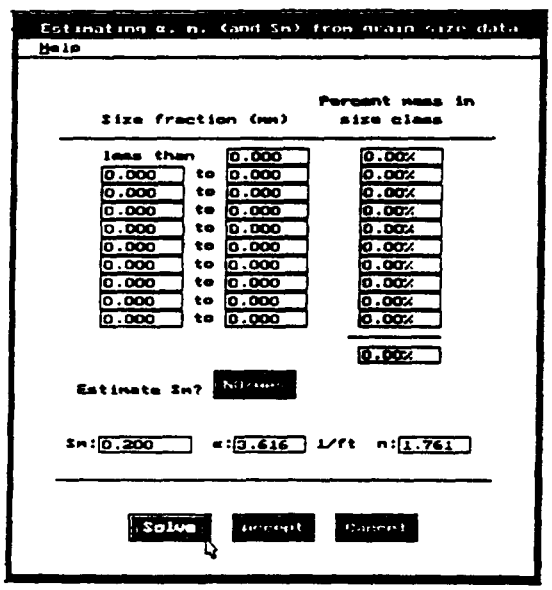
- representative values for various soils
- α from K_{rw}
- α from TPH data
- S_m from specific yield

- S_{og} from S_m
- S_{or} from S_m
- α, n, and S_m from grain size distribution data

See Section 5.4 for a discussion of each estimator.

Whichever choice you make, a dialog window appears with fields for entering data required by PreArm to do the calculation, as well as a field for displaying the results (Figure 13 shows the α, n and S_m from grain size data dialog box). Enter the required data. As you proceed with data entry, PreArm checks the data to ensure that all values are within valid ranges. If you need help at any time with soil estimators, simply press the **[Help]** button.

Figure 13



Once data entry is complete, select the **[Solve]** button. PreArm computes an estimated parameter value and displays it in a field in the lower half of the window.

If you wish to use the estimated value for future PreArm calculations, select **[Accept]**. PreArm returns you to the original data input window where the estimate is entered into the relevant field. If you choose not to use the estimated value, or wish to exit the estimator window at any time without saving estimator data, select **[Cancel]**.

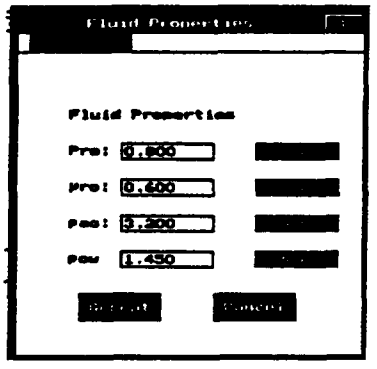
PreArm returns you to the original data input window, but the estimated value is not entered in the relevant field.

When you have finished entering parameter values in the Soil Properties window, select **[Accept]** to use these data in any further calculations, or **[Cancel]** to revert to the previous values. In either case PreArm returns you to the main menu.

3.6.4 Fluid Properties

Select the **[Fluid]** button under the Properties section of the PreArm Checklist window, to enter the fluid properties entry window (Figure 14). Oil specific gravity, oil viscosity and capillary scaling parameters used in the van Genuchten model are entered in this window.

Figure 14



Please note that you cannot change ρ_{ro} from this window, you must change it from **Database / Fluid Level / Density** or to ensure consistency with corrected watertable calculations in the database.

You may enter known parameter values and/or you may select **Estimators** from the menu. Section 3.6.6 describes how to use the fluid estimators. Following is a description of the fluid estimators:

ρ_{ro} This is the specific gravity of the hydrocarbon, i.e. the oil to water density ratio. The allowed range is $0.55 > \rho_{ro} >= 0.98$.

μ_{ro} This is the ratio of hydrocarbon viscosity to water viscosity. The allowed range is $0.1 > \mu_{ro} > 1000$.

β_{ao} This is a scaling factor for the capillary pressure relations approximated by the ratio of uncontaminated water surface tension to oil surface tension. The allowed range is $1.1 > \beta_{ao} > 5.0$.

β_{ow} This is a scaling factor for the capillary pressure relations approximated by the ratio of uncontaminated water surface tension to oil-water interfacial tension. The allowed range is $1.1 > \beta_{ow} > 50.0$.

You may also choose **Help** next to each parameter to display acceptable ranges. Note that the initial fluid parameters for a new project will all be set to zero, an invalid value for all of the parameters.

3.6.5 Entering known fluid parameter values

To input known parameter values, place the mouse cursor on the appropriate field and press the left mouse button. The data entry cursor appears. Enter the desired value using the keyboard. You can use the left and right arrow keys to move around within the data entry field, and **<Tab>**, **<Shift-Tab>** and the up and down arrow keys to move from field to field.

Selecting another field in the window will prompt PreArm to validate the contents of the previous field. If the value is valid, the cursor moves to the next field. If the value is invalid, an error message appears which must be acknowledged by selecting either the **[Cancel]** button or the **[Help]** button. The **[Help]** button opens a Help window to provide additional information on selecting the fluid parameter. Once the error message has been acknowledged (by selecting **[Cancel]**), or the Help window closed and followed by acknowledgment of the warning (by selecting **[Cancel]**), input may continue. You are not allowed to **[Accept]** the data until all values are valid. A list of valid ranges is available by selecting Help from the fluid Parameters dialog window menu.

When you have finished entering the fluid parameters, select **[Accept]** to use these data in any further calculations, or **[Cancel]** to revert to the previous values. Selecting **[Cancel]** returns you to the main menu and any changes you have made are not saved. If you choose **[Accept]**, PreArm returns you to the main menu, after saving your changes.

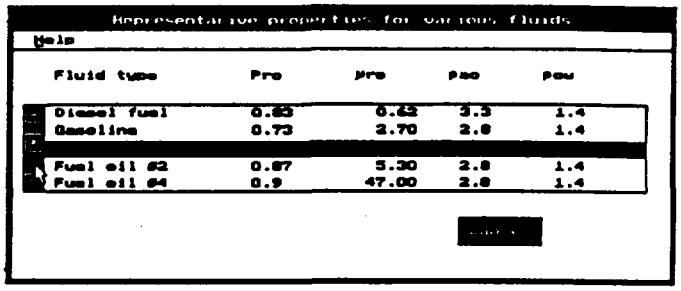
3.6.6 Estimating fluid parameter values

If you are unsure of a fluid parameter value, or you do not understand what data is being requested, PreArm can assist you.

Choosing **Estimators** produces a drop-down menu of property estimators that may be used to compute various fluid parameters.

Selecting the first choice in the estimator drop-down menu brings up a list box of representative fluid types and their corresponding parameter values (Figure 15). The scroll bar on the left of the display allows you to navigate the list.

Figure 15



To choose one of the items in the list, place the mouse cursor on it and click the left mouse button. This closes the window and enters the values in the corresponding column of the Fluid Properties window.

To exit this window without making a selection, click on **[Cancel]**.

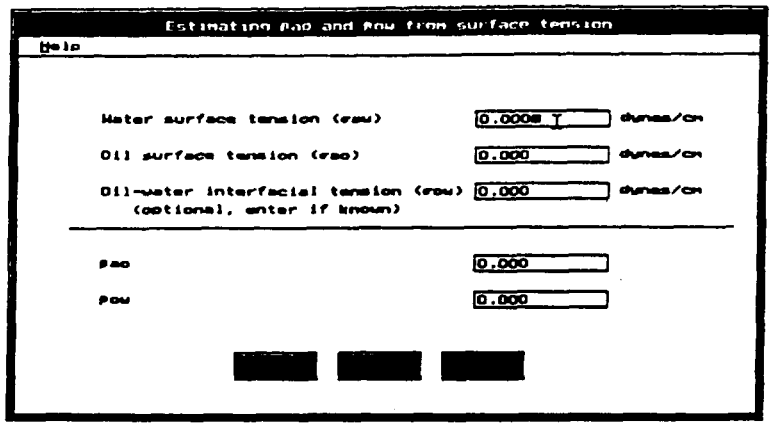
If you do not wish to select a fluid from the list of representative fluids, an alternative is to estimate individual fluid parameters by giving PreArm certain data from which fluid parameters may be estimated.

Your choice of estimators supported by PreArm is as follows:

- Representative values for various fluids
- Estimation of β_{ao} and β_{ow} from surface tension
- Estimation of β_{ao} and β_{ow} from crude oil density

Whichever choice you make, a dialog box appears with fields for entering data required by PreArm to do the calculation, as well as a field for displaying the results (Figure 16). Enter the required data. As you proceed with data entry, PreArm checks the data to ensure that all values are within valid ranges.

Figure 16



Once data entry is complete, select the **[Solve]** button. PreArm computes an estimated parameter value and displays it in a field in the lower half of the window.

If you wish to use the estimated value for future PreArm calculations, select **[Accept]**. PreArm returns you to the original data input window where the estimate is entered into the relevant field. If you choose not to use the estimated value, or wish to exit the estimator window at any time without saving estimator data, select **[Cancel]**. PreArm returns you to the original data input window, but the estimated value is not entered in the relevant field.

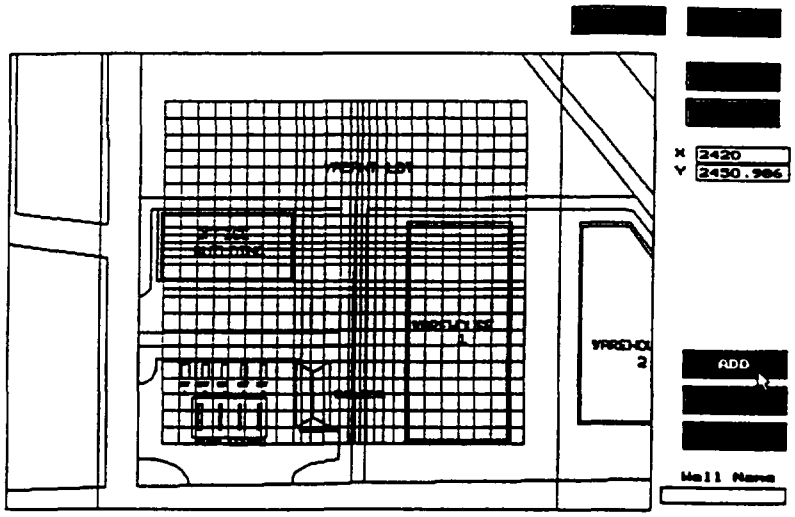
When you have finished entering parameter values in the Fluid Properties window, select **[Accept]** to use these data in any further calculations, or **[Cancel]** to revert to the previous values. In either case PreArm returns you to the main menu.

3.7 Printout Locations

Printout locations can be anywhere inside the data domain: they do not have to be on the nodes. Values of state variables like Z_{ao}, Z_{aw}, Z_{ow}, H_o, V_o, etc. (see Chapter 4) are interpolated to those locations

and printed out at every printout time. You may use the non-nodal value graphical editor to enter printout locations (Figure 17). These locations are commonly used to acquire simulation results for monitoring well locations to compare with observed data. Use **[Add]** to enter a new printout location or use **[Edit]** to edit an exiting printout location.

Figure 17



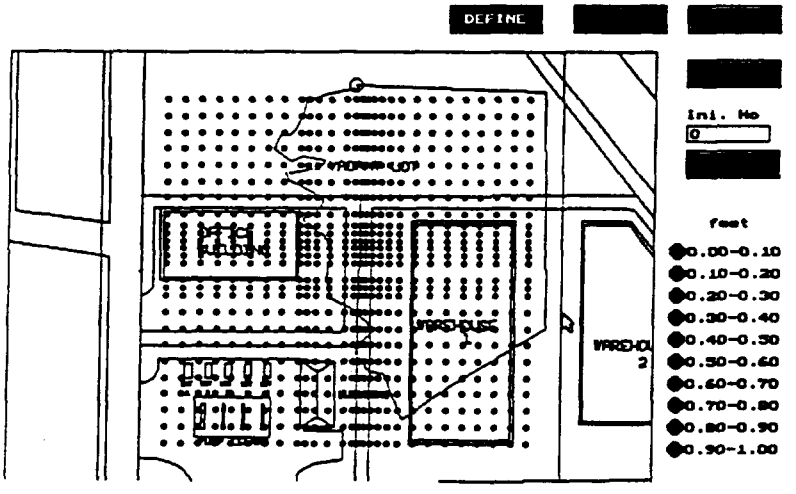
To add a location click on **[Add]**, then click on the basemap where you want a print out location to be. After selecting a location for output you may enter a name for that location. This name will be used by the Post-Processor to identify the selected locations. If desired, the X-Y location may be edited to facilitate placement at exact locations, i.e. monitoring well locations. Clicking on **[Accept]** enters the location along with its name. Locations may be removed by clicking on **[Remove]**. The **[Done]** button saves your data and exits the Printout Locations window, while the **[Cancel]** button simply exits.

3.8 Initial Conditions

Initial conditions are the fluid table elevations everywhere in the domain at the beginning of the simulation. Initial conditions for the two-phase flow model ARMOS require the air-oil table (Z_{ao}) and air-water table (Z_{aw}) to be specified for all nodes. The program uses Z_{aw} and well oil thickness (H_o) as inputs and computes initial (Z_{ao}

$= Z_{aw} + (1-\rho_{ro}) H_o$, where ρ_{ro} is the oil specific gravity). There are 3 options listed in the menu for initial conditions. Use the **Block Edit** option to enter nodal values to enter nodal Z_{aw} and H_o (Figure 18). In most cases when monitoring well data are available, use the **Measurement points** option to krige initial fluid table elevations from monitoring well data to the finite element domain. The **From the database** option retrieves data from the Fluid Level database for Z_{aw} and H_o and provides for interpolation to the finite element domain. **Restart from a previous run** is used when you are preparing a data file for a restart run. PreArm asks you to enter the name of the auxiliary output file from a previous ARMOS run, which is used to store restart data. Final fluid levels from the previous run will be used as initial conditions for the current run for a restart problem.

Figure 18



3.8.1 Ho BlockEdit

Use this button to edit nodal values of well product thickness. This window functions as does the bottom elevations block edit window (see Section 3.5.1).

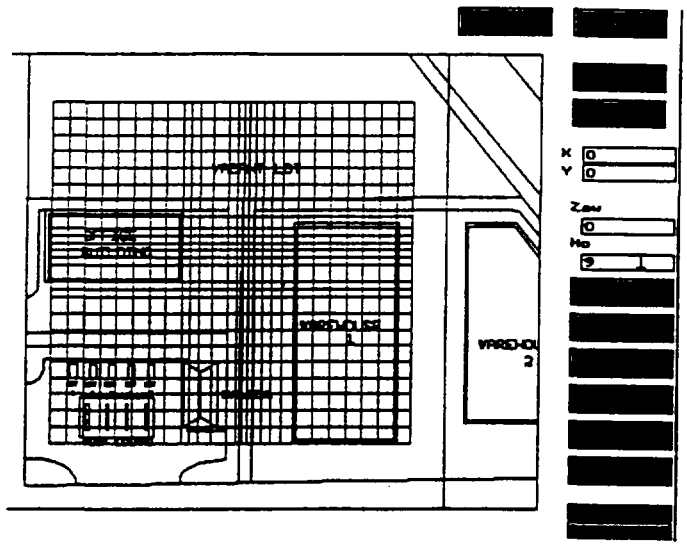
3.8.2 Zaw BlockEdit

Use this button to edit nodal values of air-water table elevations. This window functions as the bottom elevations block edit window does (see section 3.5.1).

3.8.3 Measurement points

Measurements of fluid table elevations at monitoring wells or other measurement areas are used to interpolate initial fluid table elevations to all the nodes. Measurements can be edited when this option is invoked (Figure 19).

Figure 19



Use the **[Import]** button to import data points from an ASCII file (see Appendix B for **.imp** file format). The **[Import]** button brings up the file selector box for *.imp files. Use the **[Grid Zaw]** button to contour Z_{aw} from the current set of measurement points, and **[Grid Ho]** to contour H_o from the current set of measurement points. Use the **[Add]** Button to add measurement points to the set, and the **[Edit]** button to change a value or its location. Both the **[Add]** and the **[Edit]** buttons should be followed by the **[Accept]** button to enter the changes into the selection set.

A default value of -9999 for Z_{aw} and H_o is generated for each new measurement point. Values of -9999 are not considered by PreArm to be valid data points, and are not considered when interpolating values onto the mesh for initial conditions. This feature allows data to be entered for either H_o or Z_{aw} without having to enter a value for both data types.

You can change kriging options by pressing either **[ZAW OPT]** or **[HO OPT]**. The kriging options are as follows:

Use nearest ? data points	This value specifies the number of data points that will be used to interpolate at a node (if available). The default is 15.
Search radius	This is the distance from any node that ARMOS will search for data.
Minimum value	Set this to the minimum value you want ARMOS to krige (e.g., the lowest physically meaningful or measurable value).
Value to use if less than min.	Any kriged value on the grid less than "minimum value" well be set equal to this value.
☐ Set value to ? if no points in search radius	If this box is checked, any nodes with no data points within the search radius will be assigned the specified value.
☐ Krige log transform	If this box is checked, kriging will be performed on log-transformed data. Log-transformed kriging can be useful for interpolating data such as dissolved concentrations that are noisy and have a very wide range.Any non-positive data or kriging limits will be automatically set to 10% of the minimum positive value in the data set.

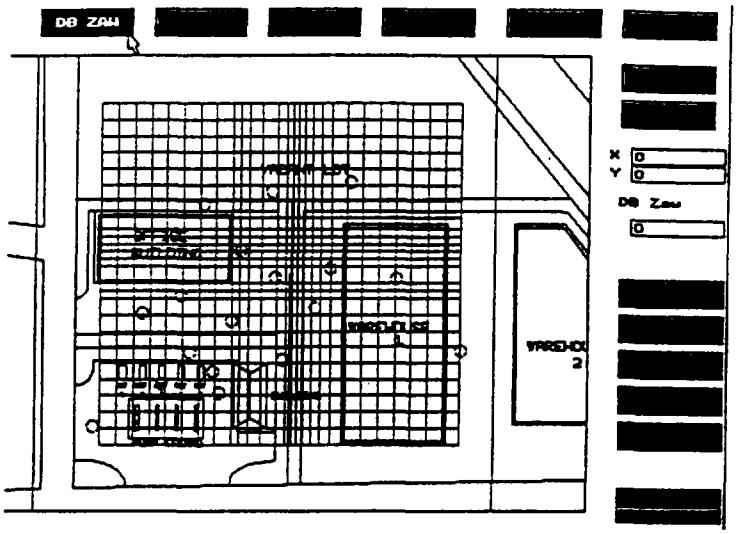
3.8.4 From the database

Use this option to extract H_o and Z_{ao}, data from the project database to estimate initial conditions for an ARMOS simulation. These values are interpolated by kriging to the finite element domain.

Selecting the **[From Database]** button brings up the date criteria selectors for PreArm to use as criteria for the extraction of points from the database. The **[Selection Method]** button in this box determines how the duplicate points (if any) that are retrieved from the database are handled. If you are just editing a previous data file

and you want to just modify the data that you have previously generated in this option select the **[Prev]** button to edit your previous data, otherwise use the **[Get]** button to retrieve the information from the database. This will bring you to the initial conditions editing screen (Figure 20). Selecting **[Cancel]** instead of **[Get]** or **[Prev]** will return you to the PreArm Checklist Window.

Figure 20



Use the **[Grid Zaw]** button to contour Z_{aw} from the current set of data points, and **[Grid Ho]** to contour H_o from the current set of data points. After gridding it may be necessary to right click the mouse in order to see the contours (if auto redraw is set to off). The four buttons at the top of the Initial Conditions window determine the type of data point that is shown on the screen (contours include both data types). There are two types of data points in database initial conditions:

1) Database points - Points that were retrieved from the database. The **[DB Zaw]** - database Z_{aw} shows all locations for data points with values that fall within the specified Z_{aw} date range. The **[DB Ho]** - database H_o shows all locations for data points with values that fall within the specified H_o date range.

2) Control points - Control points are used to fill in data gaps for kriging. These points allow the users to specify values for areas where there is no data. Sometimes this is necessary for the kriging algorithm to generate rationally distributed contours. The **[Ctrl Zaw]** - shows all locations for Z_{aw} Control points. The **[Ctrl Ho]** - shows all locations for H_o Control points.

[**Add**], [**Remove**], and [**Edit**] functions work on all four types of data. Adding or editing of points must be followed by clicking on the [**Accept**] button to enter the data modifications into the data set. After the data set has been modified you must use the [**Grid Zaw**] and [**Grid Ho**] buttons for the changes to be reflected in the contours. The [**Done**] button exits the initial conditions screen, saves your changes, and returns you to the PreArm Checklist window, while the [**Cancel**] button simply returns you to the PreArm Checklist window.

You can change kriging options by pressing either [**ZAW OPT**] or [**HO OPT**]. See Section 3.8.3 for a description of these options.

3.8.5 Restart file

If the current ARMOS problem is a restart from a previous run, clicking on the [**Restart File**] button brings up the file selector box. Select the name of the previous run, the last time-step of which will be used to define the initial conditions for the current problem.

3.9 Boundary Conditions

ARMOS employs boundary condition "schedules" as a flexible and simple means of specifying time varying values of elevations and flow rates. Schedules are simply table of boundary condition values (e.g., table elevation, flow rates, etc.) versus time that ARMOS uses to generate piecewise linear continuous functions for boundary conditions as they vary in time.

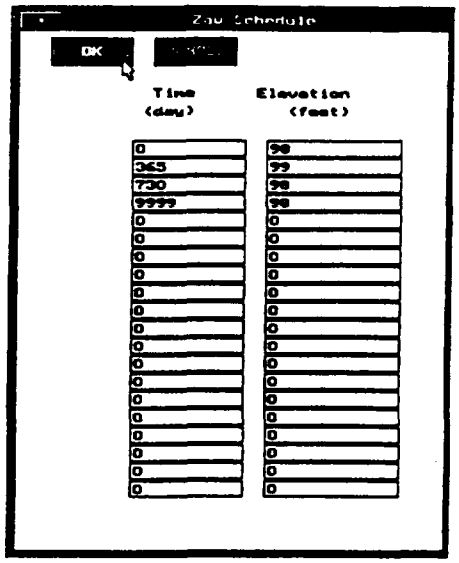
The *default* boundary condition for the perimeter of the domain in ARMOS 5.0, if no boundary conditions are specified (Z_{aw} or boundary fluctuation options are not checked off in the Pre-processor checklist), is a *no flow boundary*. If boundary conditions are specified on only part of the domain perimeter, the rest of the perimeter nodes are treated as the default no flow condition.

3.9.1 Zaw

This option may be used to specify values at nodes on the boundary as well as nodes internal to the domain. Specified Z_{aw} boundary conditions take precedence over all other boundary conditions.

Click on [**Zaw**], and the window for specifying Z_{aw} nodes will be opened. To define a specified-head, click on [**Add**] and then click on the desired node (Figure 21). A schedule window will pop up for inputting a schedule for the node. If you want specify a group of nodes with the same boundary schedule, use [**Copy**]. To edit an existing schedule use the [**Edit**] and [**Move**] buttons.

Figure 21



This boundary schedule for Z_{aw} will initially fix the boundary nodes at an elevation of 98 feet. The boundary node elevations will then linearly increase from 98 feet to 99 feet over the first 365 day time period. The elevations will then linearly decrease back to 98 feet over the second 365 day time period (365 to 730 days). The elevations will then remain constant (up to day 9999, past the end of the simulation).

3.9.2 Zao

Click on [**Zao**], and the window for specifying Z_{ao} nodes will be opened. To define a specified-head node, click on [**Add**] and then click on the desired node. A schedule window will pop up for inputting a schedule for the node. If you want specify a group of nodes with same boundary schedule, use [**Copy**]. To edit an existing boundary node, you can use the [**Edit Sch**] and [**Move**] buttons.

3.9.3 Recharge

Use this option to define recharge zones and schedules for recharge rates. Areal recharge (volumetric flow rate per area) can be used for net rainfall. Units are ft/day. The Edit functions in this window function as the block edit functions discussed in section 3.5.1, except that you enter a rate schedule when the **[Edit]** button is clicked on.

3.9.4 Wells

A well node is a mixed-type internal boundary node. Well nodes on the domain perimeter will not be honored if a specified head condition is also imposed on the same node. ARMOS honors specified head conditions over other types of boundary conditions. Well node boundary conditions are defined by schedules of specified flow rates (cubic feet per day) on interior nodes versus time. If the computed pumping rate later exceeds the schedule rate, the schedule rate will be used again as long as Z_{aw} remains above the intake elevation. If the well water level reaches the user-specified pump elevation, ARMOS will fix Z_{aw} at the well node as the pump intake elevation and compute the pumping rate (schedule value is not used in this case). If the computed pumping rate is negative, which means recharge has to be applied to maintain Z_{aw} at the pump elevation, a no-flow condition will be specified until Z_{aw} at the well node goes above the pump elevation.

Oil removal is treated in a similar manner in that an oil pumping rate schedule is specified. If the pumping rate causes Z_{ao} to fall below Z_{aw}, the program automatically switches to a specified head condition with $Z_{ao} = Z_{aw}$ (i.e., $H_o = 0$) in the well and the actual oil pumping rate will be computed. If the computed rate later exceeds the scheduled rate, the schedule value will be imposed. In most cases, oil is skimmed to maintain well oil thickness near zero and the rate is not known. The input oil rate should exceed the actual rate to ensure zero thickness condition is forced. To ensure a stable solution, the specified rate may be "ramped" up from zero to a large volume over 10-20 time steps. If oil skimming is stopped later the rate schedule may be used to turn the well off.

Both Z_{ao} and Z_{aw} gradients are usually high around a well, so a finer mesh around well nodes is recommended to achieve better accuracy. ARMOS has an automatic well node mesh refinement scheme. If a minimum mesh size is specified, additional elements will be added and the size of the 4 elements surrounding the well

node will be sequentially reduced to half of the original size, until the new well node element size is less than or equal to the specified minimum. The maximum levels of mesh refinement is 3. If the node spacing of the unrefined mesh is 100 feet, three levels of refinement would produce spacings of 50, 25, and 12.5 feet with the denser spacing immediately surrounding the well. Specifying any spacing below the 12.5 foot minimum will assign a value of 12.5 to the lowest level of refinement (on a 100 foot mesh). *Also, automatic mesh refinement may not be used on adjacent nodes. There must be at least 1 node between nodes that use automatic refinement.* You may not specify a well node on the domain perimeter or on a node of a triangular element if you use automatic well node refinement. Entering a zero for mesh refinement will turn the mesh refinement scheme off for a well node.

To specify a well node, you need to enter both water pumping and oil pumping schedules. Rates are in ft^3/day. Pump elevation, well bottom elevation, mesh refinement and well name are also required for each well node. First, select a well node by clicking on it. Enter values for pump elevation, well elevation, mesh refinement (optional, 0 = off) and well name, then click on **[Assign]** to update these values for the selected well node. This assigns well bottom elevation, pump elevation and mesh refinement size to the well node. The **[Add]** button adds a new well and prompts the user for water and oil pumping schedule data. The **[Copy]** button copies an existing well. Note: the copy function creates wells that refer to the *same* schedule. If you edit a schedule for a well that shares schedules with another well, you will affect those changes to both wells. **[Ed Water]** allows for editing a previously defined water pumping schedule for a well, while the **[Ed Oil]** button allows for editing a previously defined oil pumping rate schedule. Below is the pumping schedule for a well from the tutorial problem in Chapter 7.

Time (Days)	**Rate (ft^3/day)**
0.0	0.0
1.0	288.7
99999.0	288.7

The above schedule gradually turns on the pump over the first day of the simulation. "Ramping" of schedules in this manner is recommended, because it reduces the solution nonlinearity. The longer the ramping period the more linear the solution becomes.

The [Done] button exits the Wells window, saves your changes, and returns you to the PreArm Checklist window, while the [Cancel] button simply returns you to the PreArm Checklist window.

3.9.5 Boundary Node Fluctuation

For perimeter nodes, a prescribed water level (Z_{aw}) can be imposed which equals the initial value plus a time-dependent change defined in a fluctuation schedule. Keep in mind that specified Z_{aw} boundary conditions take precedence over initial and fluctuation schedules. You may use a combination of these options by specifying Z_{aw} at some boundary nodes and using a fluctuation schedule for the rest of the nodes.

For example, the fluctuation schedule for a 360 day period is given by the following four sub-schedules:

Time (days)	Elevation (feet)
0 (days)	0.0
90	1.0
270	-1.0
360	0.0

which indicates that the water table elevations at each node on the perimeter linearly rise from the initial value to one foot higher over the first 90 days, then gradually fall to one foot below the initial levels between 90 and 270 days (at 180 days the levels will be equal to the starting values), and finally between 270 and 360 days the levels rise back to the starting values again. For example, if the initial Z_{aw} at perimeter node I is 100 feet, then the internally computed boundary condition schedule imposed on node I will be:

Time	Elevation (feet)
0 (days)	100.0
90	101.0
270	99.0
360	100.0

The schedules for all other perimeter nodes will be similarly computed. Note that a constant water table may be imposed using the following fluctuation schedule:

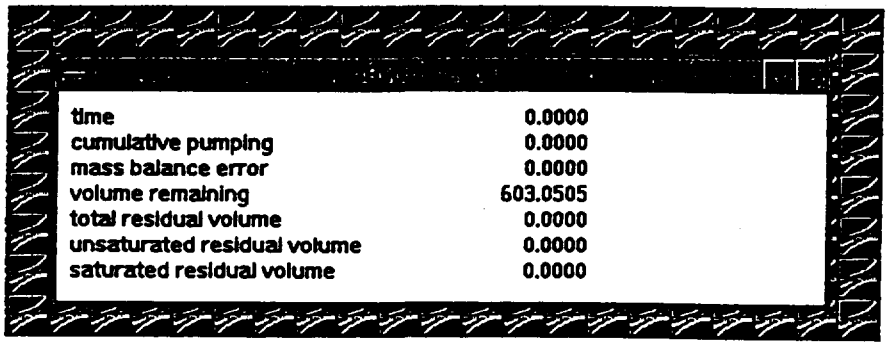
0	0.0
9999	0.0

If no fluctuation schedule is stipulated the default boundary condition on the model perimeter is no flow.

3.10 ARMOS Run Module

After you have completed the Pre-processor checklist, choose **Model / Run** from PreArm. This will prompt you for a file name. After you have entered a name for the run, minimize PreArm and double-click RunArm from the ES&T icon group in Windows® or run ARMOS5 from DOS by typing **armos5** at a DOS prompt. Both DOS ARMOS and RunArm will execute the last datafile selected in **Models / Run** in PreArm. Because RunArm is a true Windows application, it may be minimized to run in the background while you work on something else. Figure 22 shows the Windows® RunArm module.

Figure 22



3.11 ARMOS Post-processor

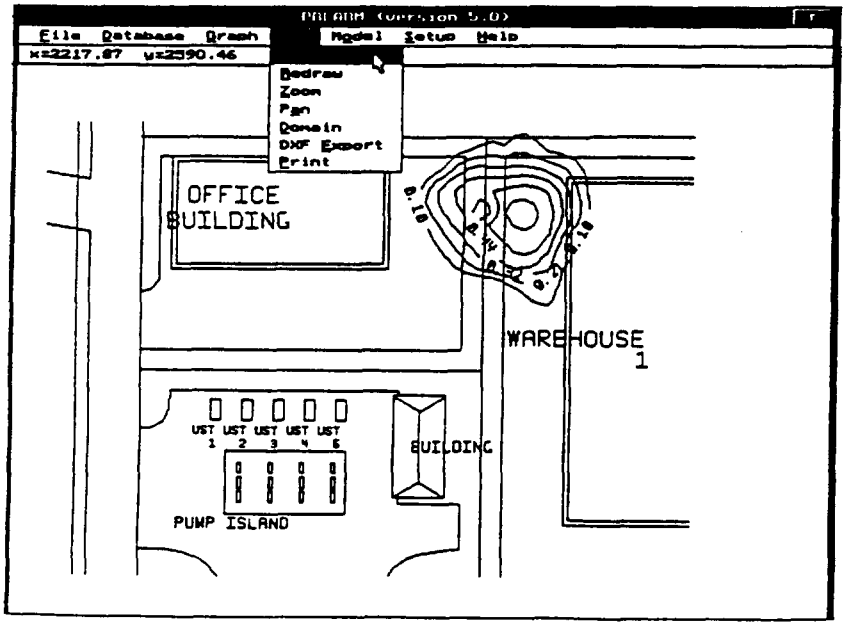
After the run is complete, return to PreArm and select **Model / Post-processor** from the main menu. Select the file name you entered for the run.

You can add overlays of the following items:

Q_w	Water Darcy velocity
Z_{aw}	air-water table elevation (ft)
Z_{ow}	oil-water table elevation (ft)
Z_{ao}	air-oil table elevation (ft)
H_o	well product thickness (ft)
V_o	total oil volume per area (ft)
V_{of}	free oil volume per area (ft)
V_r	residual oil volume per area (ft)

To contour any of these values, select a time-step by clicking on the triangle beside **Time:** (this drops down a list of output times available for contouring), then on the desired time step. Click on the box next to the item you wish to contour, then on **[Add to overlay]**. When you exit the Post-processor you can adjust the settings on the contours by selecting **Map / Overlay / Setting** then the item desired. Figure 23 shows H_o contours for the tutorial problem described in Chapter 7.

Figure 23



Nodal data (which are necessary to create contours) are available at all print out times only if you turned on the switch for nodal output in PreArm's Pre-processor. Otherwise contour plots are only available at initial and final time-steps.

For the selected printout locations, time series of the following variables can be plotted:

Z_{aw}	air-water table elevation (ft)
Z_{ao}	air-oil table elevation(ft)
H_o	well product thickness (ft)
V_o	total oil volume per area (ft)
V_{of}	free oil volume per area (ft)

For each recovery well the following time series can be plotted:

water pumping rate (ft^3/day)
oil pumping rate (ft^3/day)
cumulative water recovery (ft^3)
cumulative oil recovery (ft^3)

To graph any of these items click on the box next to the desired item, then click on the triangle beside **Location:**. Click on the location you want to graph, then click on **[View]**. If you would like to change the look of the graph, hold down the left **<Shift>** key and click the left mouse button. See Chapter 2 for an explanation of the Graph Settings dialog box.

You can also view time series graphs for the following variables:

total spill volume (ft^3)
cumulative oil recovery (ft^3)
total residual oil volume in the saturated zone (ft^3)
residual oil volume in the unsaturated zone (ft^3)
residual oil volume in the saturated zone (ft^3)
free oil area (ft^2)
total spill area (ft^2)

To graph any of these items click on the box next to the desired item, then click on **[View]**. To edit your graph hold down the left **<Shift>** key and click the left mouse button. See Chapter 2 for an explanation of the Graph Settings dialog box.

4. Modeling Approach

Three-dimensional models for multiphase flow are generally too computationally intensive for practical use in site assessment and in design of hydrocarbon spill control and recovery systems. Two-dimensional areal multiphase flow models, based on the assumption of local vertical equilibrium, have been used for many years to model petroleum reservoirs (*e.g., Martin*, 1968), and more recently have been applied to hydrocarbon spills in groundwater systems (*Hochmuth and Sunada*, 1985; *Kaluarachchi et al.*, 1990). Because vertical integration reduces the degree of nonlinearity as well as the dimensionality, computational effort becomes quite tractable with modest computer resources.

In this chapter, we describe the mathematical basis of ARMOS, including the underlying assumptions, applicability and limitations, and the numerical methods that are employed to solve the governing equations.

4.1 Three Dimensional Flow Equations

Our starting point is the description of multiphase flow in three dimensions, including vertical flow, as discussed by many authors (*Abriola and Pinder*, 1985; *Faust*, 1985; *Osborne and Sykes*, 1986; *Kaluarachchi and Parker*, 1989; *Katyal et al.*, 1992). Darcy's law may be generalized to describe flow of fluids in a multiphase system with air, water and a nonaqueous phase liquid, which we will refer to hereafter simply as "oil." The equations of motion for the water and oil phases are

$$q_{w_i} = -K_{wij}\left(\frac{\partial h_w}{\partial x_j} + \frac{\partial Z}{\partial x_j}\right) \tag{4.1a}$$

$$q_{o_i} = -K_{oij}\left(\frac{\partial h_o}{\partial x_j} + \rho_{ro}\frac{\partial Z}{\partial x_j}\right) \tag{4.1b}$$

where x_j are Cartesian spatial coordinates (j=1,2,3), q_{w_i} and q_{o_i} are Darcy velocities in the i-direction for water and oil phases [LT^{-1}], h_w and h_o are water height-equivalent pressure heads in water and oil

[L] of the form $h_p = P_p/\rho_w g \quad (p = o, w)$, where P_p is the phase pressure [FL^{-2}], ρ_w is the density of water [ML^{-3}], and g is gravitational acceleration [LT^{-2}], K_p is the p-phase conductivity [LT^{-1}], ρ_{ro} is the ratio of oil to water density [L^0], and Z is elevation. We may write an equation of the same form as (4.1b) for gas phase flow. However, we restrict our attention here to cases where it is reasonable to assume that gas pressure gradients are negligible due to atmospheric boundary control and low gas impedance– thus avoiding explicit consideration of gas flow.

Assuming negligible compressibility of the porous medium, water and oil, the liquid phase continuity equations may be written in summation convention as

$$\phi \frac{\partial S_w}{\partial t} = -\frac{\partial q_{w_i}}{\partial x_i} + J_w \qquad (4.2a)$$

$$\phi \frac{\partial S_o}{\partial t} = -\frac{\partial q_{o_i}}{\partial x_i} + J_o \qquad (4.2b)$$

where ϕ is porosity, S_p is the p-phase saturation [L^3L^{-3}] (p = o,w), t is time [T], x_i are the Cartesian spatial coordinates [L] (i = 1,2,3), and J_p are p-phase volumetric source-sink terms [$L^3\ L^{-3}\ T^{-1}$]. Repeated subscripts in (4.1) and (4.2) imply summation.

4.2 Vertical Equilibrium Head Distributions

To evaluate the vertical distribution of oil and water under conditions of local vertical equilibrium, we introduce the concept of piezometric heads for water and oil phases as

$$\psi_w = h_w + Z \qquad (4.3a)$$

$$\psi_o = h_o + \rho_{ro} Z \qquad (4.3b)$$

where ψ_w and ψ_o are water and oil piezometric heads, and Z is elevation above an arbitrary datum. Here, we consider the situation in which we can regard liquid velocities in the vertical direction as

small relative to those in the horizontal. More specifically, we assume that vertical fluid redistribution occurs on a time scale sufficiently short that vertical pressure distributions are always close to hydrostatic conditions. As we will discuss in Chapter 5, deviations from true vertical equilibrium may be expected, especially in the unsaturated zone. However, these deviations may be accommodated by suitable definition of "pseudo-equilibrium" capillary pressure relations.

In these circumstances, it is possible to characterize the vertical pressure distributions in all phases, in terms of various fluid "table" elevations. Consider a locally static system containing air, water, and less-dense-than-water oil, in which we install a screened well (Figure 1). We observe an oil lens in the well, which we may characterize by an air-oil table elevation, Z_{ao} (where the air and oil pressures are equal), and an oil-water table elevation, Z_{ow} (where water and oil pressures are equal). We may also define an air-water table elevation, Z_{aw} (where the air and water pressures are equal). Hydrostatic conditions require that $\partial\psi_w/\partial Z = 0$ and $\partial\psi_o/\partial Z = 0$, hence

$$\psi_w = Z_{aw} \tag{4.4a}$$

$$\psi_o = \rho_{ro} Z_{ao} \tag{4.4b}$$

and therefore

$$h_w = Z_{aw} - Z \tag{4.5a}$$

$$h_o = \rho_{ro}(Z_{ao} - Z)\,. \tag{4.5b}$$

From (4.5) and the definitions of Z_{aw}, Z_{ao}, and Z_{ow}, we see that the various table elevations are related by

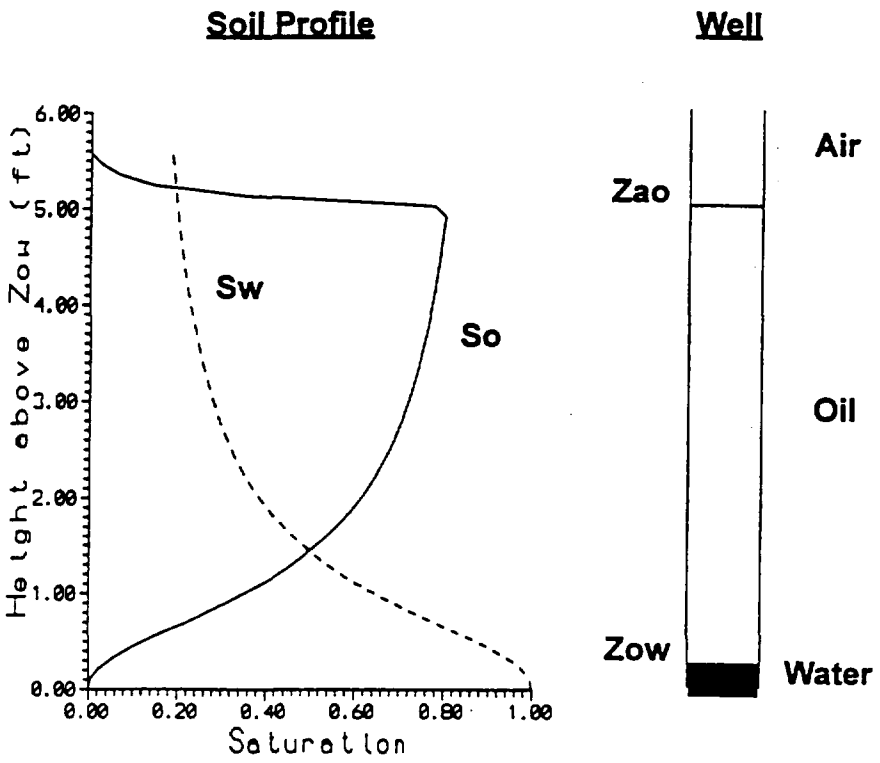
$$Z_{aw} - Z_{ow} = \rho_{ro} H_o \tag{4.6a}$$

where H_o is the apparent oil thickness defined by

$$H_o = Z_{ao} - Z_{ow} \qquad (4.6b)$$

Hence, stipulation of any two of the three table elevations completely defines the three phase static vertical head distributions. Note that if a well exists at a given location and it is in equilibrium with the soil, then H_o is the oil thickness in the well. If no well exists, H_o and the various fluid table elevations can of course still be defined. In both cases, the apparent oil thickness does not correspond directly to the oil-bearing zones in the soil due to capillary effects, discussed in Chapter 5.

Figure 1



Three phase fluid distributions in equilibrium with a screened well.

4.3 Vertical Integration of Flow Equations

Let us assume that our interest is in a flow domain bounded at the top by the atmosphere and at the bottom by the lower boundary of an unconfined aquifer. We designate the elevations of these physical boundaries as Z_u and Z_l, respectively. As discussed by *Parker and Lenhard* (1988), vertical integration of Darcy's equation (4.1), subject to the assumption of local vertical equilibrium represented by (4.5), yields

$$Q_{w_i} = -T_{w_{ij}} \frac{\partial Z_{aw}}{\partial x_j} \tag{4.7a}$$

$$Q_{o_i} = -T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_j} \tag{4.7b}$$

where Q_{w_i} and Q_{o_i} are vertically integrated fluxes [$L^2\ T^{-1}$] of water and oil in the i-direction ($x_i = x, y$) of the form

$$Q_{p_i} = \int_{Z_l}^{Z_u} q_{p_i} dZ \tag{4.8}$$

and transmissivities are defined by

$$T_{w_{ij}} = \int_{Z_l}^{Z_u} K_{w_{ij}} dZ \tag{4.9a}$$

$$T_{o_{ij}} = \rho_{ro} \int_{Z_l}^{Z_u} K_{o_{ij}} dZ \tag{4.9b}$$

where conductivities refer to horizontal values if the system is anisotropic, since Q_{p_i} describes flow in the horizontal direction. To interpret Q_{p_i}, note that it corresponds to the volume of flow in the horizontal i-direction per unit time per unit length horizontally perpendicular to the i-direction (for example, volume of flow through a boundary per length of boundary perimeter). Integrating the continuity equations (4.2) over the vertical domain likewise yields

$$\frac{\partial V_w}{\partial t} = -\frac{\partial Q_{w_i}}{\partial x_i} + \bar{J}_w \tag{4.10a}$$

$$\frac{\partial V_o}{\partial t} = -\frac{\partial Q_{o_i}}{\partial x_i} + J_o \qquad (4.10b)$$

where V_w and V_o are total water and oil volumes per horizontal area [L] at a point in the x-y plane (*fluid specific volumes*) defined by

$$V_w = \int_{Z_l}^{Z_u} \phi S_w dZ \qquad (4.11a)$$

$$V_o = \int_{Z_l}^{Z_u} \phi S_o dZ \qquad (4.11b)$$

and $\bar{J}_w$ and $\bar{J}_o$ are vertically integrated source-sink terms [LT^{-1}]. Combining (4.7) and (4.10) yields the governing equations for areal flow of water and oil as

$$\frac{\partial V_w}{\partial t} = \frac{\partial}{\partial x_i}\left(T_{w_{ij}} \frac{\partial Z_{aw}}{\partial x_j}\right) + \bar{J}_w \qquad (4.12a)$$

$$\frac{\partial V_o}{\partial t} = \frac{\partial}{\partial x_i}\left(T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_j}\right) + \bar{J}_o \qquad (4.12b)$$

In general, V_w and V_o are functions of both Z_{aw} and Z_{ao}, and the left-hand sides of (4.12a) and (4.12b) may be expanded as

$$\gamma_{ww}\frac{\partial Z_{aw}}{\partial t} + \gamma_{wo}\frac{\partial Z_{ao}}{\partial t} = \frac{\partial}{\partial x_i}\left(T_{w_{ij}} \frac{\partial Z_{aw}}{\partial x_j}\right) + \bar{J}_w \qquad (4.13a)$$

$$\gamma_{ow}\frac{\partial Z_{aw}}{\partial t} + \gamma_{oo}\frac{\partial Z_{ao}}{\partial t} = \frac{\partial}{\partial x_i}\left(T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_i}\right) + \bar{J}_o \qquad (4.13b)$$

with capacity coefficients defined by

$$\gamma_{pq} = \partial V_p / \partial Z_{aq} \qquad (4.14)$$

in which $p, q = o, w$ are phase indices. At this point, we observe that (4.13a) and (4.13b) are coupled through the time-derivative terms,

and we will later see that coupling also occurs through the transmissivity terms. However, while the coefficients in (4.13b) are highly dependent on Z_{aw}, those in (4.13a) depend little on Z_{ao}. Therefore, we invoke a simplification in (4.13) that will materially reduce the computational effort involved in solving the coupled flow equations.

Specifically, we assume that water specific volume, V_w, can be satisfactorily approximated as a function of only Z_{aw}, such that (4.13a) takes the simplified form

$$\phi_e \frac{\partial Z_{aw}}{\partial t} = \frac{\partial}{\partial x_i}\left(T_{w_{ij}} \frac{\partial Z_{aw}}{\partial x_j} \right) + \bar{J}_w \qquad (4.15)$$

where ϕ_e is the specific yield of the unconfined aquifer. Note that this is the conventional form of the water flow equation for unconfined flow, in which it is assumed that we can take specific yield as a constant, (that is, $\partial V_w/\partial Z_{aw} = \phi_e$).

4.4 Governing Equations for Areal Flow

For the purpose of formulating the numerical solution, we will write the final flow equations for water and oil with explicit consideration of point sources for water and oil, as

$$\phi_e \frac{\partial Z_{aw}}{\partial t} + \sum_{k=1}^{N_w} R_w \, \delta(x - x_k) \, \delta(y - y_k) - \frac{\partial}{\partial x_i}\left(T_{w_{ij}} \frac{\partial Z_{aw}}{\partial x_j} \right) = 0 \qquad (4.16a)$$

$$\gamma_{ow} \frac{\partial Z_{aw}}{\partial t} + \gamma_{oo} \frac{\partial Z_{ao}}{\partial t} + \sum_{k=1}^{N_o} R_o \delta(x - x_k) \, \delta(y - y_k) - \frac{\partial}{\partial x_i}\left(T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_j} \right) = 0 \qquad (4.16b)$$

where x_i (or x_j) is the spatial coordinate in the i- (or j-) direction (i,j=1,2), t is time, Z_{ao} is the elevation where the air-oil capillary pressure is zero (air-oil table), Z_{aw} is the elevation where the air-water capillary pressure is zero (air-water table), $T_{o_{ij}}$ and $T_{w_{ij}}$ are

water and oil transmissivities, ϕ_e is specific yield, γ_{pq} are oil phase capacity coefficients and N_w and N_o are the number of source/sink nodes for water and oil, respectively. Recharge or removal of water at a prescribed volumetric rate, R_w $[L^3\ T^{-1}]$, or of oil at rate, R_o $[L^3\ T^{-1}]$ is considered for locations at coordinates x_k and y_k, which may include pumping wells or recharge/leak locations (negative rates for recharge and positive for sinks). Sources or sinks are allocated to points via the Dirac delta function, $\delta(x)$.

The governing equations are subjected to the following initial and boundary conditions

$$Z_{aw}(x_i,0) = Z_{w1}(x_i) \qquad \text{for } t = 0 \text{ in } R \qquad (4.17a)$$

$$Z_{ao}(x_i,0) = Z_{o1}(x_i) \qquad \text{for } t = 0 \text{ in } R \qquad (4.17b)$$

$$Z_{aw}(x_i,t) = Z_{w2}(t) \qquad \text{for } t > 0 \text{ in } S_{w1} \qquad (4.17c)$$

$$Z_{ao}(x_i,t) = Z_{o2}(t) \qquad \text{for } t > 0 \text{ in } S_{o1} \qquad (4.17d)$$

$$T_{wn}\frac{\partial Z_{aw}}{\partial x_n} = Q_w(t) \qquad \text{for } t > 0 \text{ in } S_{w2} \qquad (4.17e)$$

$$T_{on}\frac{\partial Z_{ao}}{\partial x_n} = Q_o(t) \qquad \text{for } t > 0 \text{ in } S_{o2} \qquad (4.17f)$$

where (4.17a) and (4.17b) describe the initial conditions for water and oil within the flow domain R, (4.17c) and (4.17d) describe type-1 boundary conditions an regions S_{w1} and S_{o1} including interior prescribed-head nodes, and (4.17e) and (4.17f) describe flux boundary conditions for water and oil phases at applied fluxes of Q_w and Q_o on boundaries segments S_{w2} and S_{o2}, respectively, where x_n denotes the direction normal to the boundary, and T_{wn} and T_{on} are transmissivities in the direction normal to the boundary. Areal flow velocities $[L^3L^{-1}T^{-1}]$ for water (Q_{w_i})and oil (Q_{o_i}) are given by (4.7a) and (4.7b).

4.5 Finite Element Formulation

A Galerkin finite element method is used to solve the flow equations. The basic solution algorithm for ARMOS is as follows:

1. Solve water equation for Z_{aw} for new time using previous time-step oil-water table to compute water transmissivity (skip Step 1 if water flow is steady state).

2. Solve oil flow equation for Z_{ao} using $\partial Z_{aw}/\partial t$ from Step 1 as a known vector.

3. Increment time and proceed to next time step.

ARMOS may also be used to solve the water flow equation only (i.e., step 1). The finite element formulations for the oil and water equations are essentially identical to each other, except that the water equation contains no time derivative term for the oil phase. To simplify the description, the discussion below is limited to the solution of the oil flow equation. The solution procedure for the water equation is performed in an analogous manner. Assuming linear shape functions to describe nodal table elevations, Z_{ao} is approximated as

$$Z_{ao}(x, y, t) = \sum_{I=1}^{M} N_I(\varepsilon,\eta) Z_{aoI}(t) \qquad (4.18)$$

where N_I are the linear shape functions describing Z_{ao} within an element, ε and η are local coordinates for a given element, Z_{aoI} are nodal values of Z_{ao}, and M is the number of nodes in an element.

Using Galerkin's weighted residual approximation with weighting functions, W_I, to weight spatial dependent terms, (4.18) is written as

$$\int_{R_e} W_I \frac{\partial}{\partial x_i}\left(T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_j}\right) dR - \int_{R_e} N_I \gamma_{ow} \frac{\partial Z_{aw}}{\partial t} dR$$

$$- \int_{R_e} N_I \gamma_{oo} \frac{\partial Z_{ao}}{\partial t} dR - \int_{R_e} N_I R_o \delta(x - x_k)\, \delta(y - y_k)\, dR = 0 \qquad (4.19)$$

Further simplification of (4.19) using Green's theorem and boundary conditions given by (4.17) yields in matrix form

$$[A]\{Z_{ao}\} + [B]\left(\frac{dZ_{ao}}{dt}\right) = \{F\} \tag{4.20a}$$

where

$$A_{IJ} = \sum_{e=1}^{n} \int_{R_e} T_{o_{ij}} \frac{\partial W_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} dR \tag{4.20b}$$

$$B_{IJ} = \sum_{e=1}^{n} \int_{R_e} \gamma_{oo} N_I N_J dR \tag{4.20c}$$

$$F_I = \sum_{e=1}^{n} \left(\int_{S_e} W_I Q_{on} dS + \int_{R_e} N_I R_o \delta(x - x_k)\, \delta(y - y_k)\, dR \right)$$

$$- \frac{\partial Z_{aw_I}}{\partial t} \sum_{e=1}^{n} \int_{R_e} \gamma_{ow} N_I N_J dR \tag{4.20d}$$

$$Q_{on} = n_i T_{o_{ij}} \frac{\partial Z_{ao}}{\partial x_j} \tag{4.20e}$$

where n is the total number of elements, S_e refers to the segment of an element where flux-type boundary conditions prevail, and R_e is the element area. $n_i (i = x,y)$ is a unit vector normal to the element boundary.

In element integration, soil properties are evaluated at Gauss points interpolated by linear shape functions, for example, for the oil storage coefficient

$$\gamma_{oo}(x_g, y_g, t) = \sum_{g=1}^{M} N_g \gamma_{oo_l} \tag{4.21}$$

where γ_{ool} is the nodal value of γ_{oo}, and N_g is the basis function at the Gauss point. Adopting this procedure with all other soil properties, it is possible to evaluate the influence coefficient matrices for the

integrals in (4.20). For linear rectangular elements with sides parallel to the principle axes, (4.20b) may be written as

$$A_{IJ} = \sum_{e=1}^{n} \left(\sum_{g=1}^{M} \int_{R_e} N_g T^g_{o_{ij}} \frac{\partial W_I}{\partial x_i} \frac{\partial N_J}{\partial x_j} dR_e \right). \tag{4.22}$$

Following a similar procedure for (4.20c) and (4.20d), we obtain

$$[A]^e = \frac{m}{d} \sum_{g=1}^{M} [U^x]^e_g T^g_{o_{ww}} + \frac{d}{m} \sum_{g=1}^{M} [U^y]^e_g T^g_{o_{yy}} + [U^{xy}]^e T^g_{o_{xy}} + [U^{yx}]^e T^g_{o_{xy}} \tag{4.23a}$$

$$[B]^e = \frac{md}{4} \sum_{g=1}^{M} [V]^e_g \gamma^g_{oo} \tag{4.23b}$$

$$[E]^e = \frac{md}{4} \sum_{g=1}^{M} [V]^e_g \gamma^g_{ow} \tag{4.23c}$$

where d and m are element dimensions in the x and y directions, respectively, $[U^x]$, $[U^y]$ and $[V]$ are influence coefficient matrices (*Kaluarachchi and Parker*, 1988), and g indicates parameters evaluated at Gauss points. Due to the mild nonlinearity of the vertically integrated flow model, we do not use upstream weighting, thus W_I and N_I are identical functions.

For flux boundary conditions, the matrix $\{F\}$ of the original finite element formulation is modified as

$$\int_{S_e} W_I Q dS = \frac{l}{6} \begin{bmatrix} 2Q_1 + Q_2 \\ Q_1 + 2Q_2 \\ 0 \\ 0 \end{bmatrix} \tag{4.24}$$

where Q_1 and Q_2 are applied normal fluxes at nodes 1 and 2 of a given side of an element for a particular phase, and l is the length of the side.

In addition to the analytical integration for rectangular elements described above, ARMOS also allows use of irregular quadrilateral and triangular elements, in which case A_{IJ}, B_{IJ}, and F_I are evaluated numerically.

4.6 Treatment of Nonlinearities

The time derivative term in (4.20) is written in finite difference form by

$$\left(\theta\,[A] + \frac{[B]}{\Delta t_{k+1}}\right)^{k+\theta}\{Z_{ao}\}^{k+1} = \left(\frac{B}{\Delta t_{k+1}} + (\theta - 1)\,[A]\right)\{Z_{ao}\}^{k} + \{F\}^{k+\theta} \tag{4.24a}$$

$$\{Z_{ao}\}^{k+\theta} = \theta\,\{Z_{ao}\}^{k+1} + (1-\theta)\,\{Z_{ao}\}^{k} \tag{4.24b}$$

in which k and k+1 denote the previous and current time levels, Δt_{k+1} is the current time-step, and θ is a time-weighting factor. For the most stable numerical solution, θ=1 is used, corresponding to the fully-implicit backward difference scheme. Convergence of the nonlinear iterations for the water and oil equations is determined by the criteria

$$\left|Z_{aw}^{r+1} - Z_{aw}^{r}\right| \le \varepsilon_w \tag{4.25a}$$

$$\left|Z_{ao}^{r+1} - Z_{ao}^{r}\right| \le \varepsilon_o + \varepsilon_{ro} d_o^{r} \tag{4.25b}$$

where r and r+1 denote the previous and current iterations at time-step k+1, ε_w and ε_o are user-specified absolute convergence criteria for the air-water and air-oil tables, ε_{ro} is a relative convergence criterion for the oil phase fixed at 0.005, and $d_o^r = Z_{ao}^{r+1} - Z_{aw}^{r+1}$. At each iteration, a relaxation scheme is used to improve convergence behavior.

For most nonlinear flow problems, the use of a consistent mass matrix for integrals given by (4.20) causes instability in the solution that leads to poor convergence. To obtain a more stable solution, a common approach is to diagonalize the mass matrix - a procedure referred to as mass lumping. The procedure used in the present study is given for (4.20c) as

$$B_{IJ} = \sum_{e=1}^{n} \sum_{g=1}^{M} \left(\int R_e N_g N_I dR \right) \gamma_{ww}^{g} \qquad \text{for } I = J \qquad (4.26)$$

$$= 0 \qquad \text{for } I \neq J$$

A similar procedure is followed for (4.20d).

4.7 Solution of Linearized Equations

The assembled system of linear equations is sparse, with only a few nonzero coefficients per line. Because ARMOS uses an advanced indexing technique for storing data in the global matrix, there is no limit on the band width, so nodes do not need to be renumbered to optimize band width when a complex mesh is created. ARMOS utilizes three different iterative solvers and selects the most suitable solver for a given iteration to provide optimum efficiency based on the characteristics of the matrix. The three solvers are (1) Jacobi, (2) Frankel-Young, and (3) Conjugate Gradient. Each is briefly described below.

Jacobi Method. In the Jacobi method, the matrix is decomposed as the sum of three matrices as

$$\mathbf{A} = \mathbf{L} + \mathbf{D} + \mathbf{U} \qquad (4.27)$$

where

$$\mathbf{L} = \mathrm{M}_{ij} \; (j<i) \qquad (4.28a)$$

$$\mathbf{D} = \mathrm{M}_{ii} \qquad (4.28b)$$

$$\mathbf{U} = \mathrm{M}_{ij} \; (j>i) \qquad (4.28c)$$

To solve the system of equations $\mathbf{A}\,\mathbf{H} = \mathbf{F}$, the iterative algorithm is

$$\mathbf{H}_{n+1} = \mathbf{D}^{-1} \{\mathbf{F} - (\mathbf{L} + \mathbf{U})\, \mathbf{H}_n\} \tag{4.29}$$

where n is the iteration index.

Frankel-Young Method. In the Frankel-Young or point-successive over-relaxation (PSOR) method, the system $\mathbf{AH} = \mathbf{F}$ is decomposed as

$$(\mathbf{D} + \mathbf{L})\, \mathbf{H} = \mathbf{F} - \mathbf{U}\, \mathbf{H} \tag{4.30}$$

and the solution algorithm is

$$\mathbf{H}_{n+1} = (\mathbf{D} + \rho\, \mathbf{L})^{-1} \{[(1 - \rho)\mathbf{D} - \rho\mathbf{U}]\, \mathbf{H}_n + \rho\mathbf{F}] \tag{4.31}$$

where ρ is the over-relaxation coefficient.

Conjugate Gradient Method. In the conjugate gradient method, we define

$$\mathbf{f(X)} = 0.5\, |\mathbf{A}\, \mathbf{H} - \mathbf{F}|^2 \tag{4.32}$$

The function f reaches a minimum when X satisfied the linear set of equations $\mathbf{AH} = \mathbf{F}$. A conjugate gradient minimization will therefore solve the set of equations. The algorithm involves two steps. The first step is to calculate the gradient of the function $\nabla\mathbf{f(X)}$, and second step is to minimize f along a specified direction. The latter requires finding the value of λ that minimizes the expression

$$\mathbf{f(H} + \lambda\, \mathbf{U}) \tag{4.33}$$

where

$$\nabla\, \mathbf{f(X)} = \mathbf{A}^T (\mathbf{A}\, \mathbf{H} - \mathbf{F}) \tag{4.34a}$$

$$\lambda = \frac{-\mathbf{U}\nabla\mathbf{f}}{|\mathbf{AU}|^2} \tag{4.34b}$$

for specified **H** and where **U** is the unit matrix.

4.8 Wells and Source/Sink Nodes

Water pumping wells or trenches are treated as point sinks with a prescribed volumetric extraction rate, R_w, which may be specified by the user as a function of time. Wells must be located at nodes. Pump intake elevation, Z_{pump}, and well screen bottom elevation, Z_{ls}, are also specified for pumping wells. At each time step, the program checks whether the computed water elevation in the well is at or above Z_{pump}. If this condition is not met, then the value of Z_{aw} at the well node is set equal to Z_{pump} and the pumping rate is computed, rather than using the user-specified value. Subsequently, the computed water pumping rate is compared to the pumping rate schedule, and if the scheduled rate falls below the computed rate, the solution is recomputed using the lower value.

Oil recovery from wells or trenches, which may pump water and oil or just oil, is also modeled. Water pumping is treated independently of oil, as described above. Oil pumping rates are specified for oil recovery nodes as the lesser of 1) a user prescribed oil pumping rate, or 2) an internally computed rate that corresponds to the maximum achievable rate for the well under the current conditions. The first criteria allows the user to specify known small rates (e.g., due to bailing), or to turn recovery systems on and off. The maximum recovery rate for a recovery well is computed by specifying $Z_{ao} = Z_{ow}$ at the well node.

Point sources for water or oil may also be specified to model injection wells, leaking pipes, etc. These are handled simply as nodes with a user prescribed volumetric rate - input as a piecewise linear function of time. Distributed recharge is also modeled for water as a spatially and temporally variable flux (volumetric rate per area).

4.9 Mass Balance Calculations

For a given time-step, a small mass balance error may occur due to a discrepancy between the actual mass change over the time-step and the change computed by multiplying the head change by the mass matrix. ARMOS, however, automatically corrects for this

problem using a scaled mass matrix technique. At the end of each iteration for the oil equation, the program computes the global volumetric mass balance error for the oil phase as the difference between previous and current oil volume in the system and the cumulative net flux of oil in or out of the system. Previous and current oil volumes are computed by summing oil specific volumes multiplied by nodal areas over the domain. Cumulative net fluxes are computed by integrating boundary fluxes and source-sink rates over time. Element scale factors are computed that satisfy the mass balance in each element and the mass matrix is scaled by these factors in the next iteration. This technique ensures that negligible mass balance error will result in the oil flow solution.

5. Vertically Integrated Hydraulic Properties

In order to solve the vertically integrated oil and water flow equations presented in Chapter 4, it is necessary to characterize the functional relationships between oil and water specific volumes and transmissivities, on the one hand, and fluid table elevations on the other. ARMOS employs a model based on the three phase van Genuchten capillary function, which is simple and accurate. Parametric values are also widely tabulated for a broad range of soils.

In this chapter, we will describe the vertically integrated hydraulic property model, provide representative values of relevant parameters, and discuss methods that may be used for their determination.

5.1 Capillary Pressure-Saturation Relations

The vertically integrated constitutive model requires knowledge of the relationship between oil specific volume, V_o, and the fluid table elevations, Z_{ao} and Z_{aw}. It is useful to first distinguish between *free oil*, which is mobile, and which may be detected in monitoring wells; and *residual oil*, which is not free to move. Furthermore, we distinguish between residual oil in the liquid-saturated zone, which occurs as hydraulically discontinuous blobs trapped within the continuous water phase; and residual oil in the unsaturated zone, which occurs as thin films and as pendular rings of oil at particle contacts. The accounting for oil specific volume is thus

$$V_o = V_{of} + V_{or} \tag{5.1a}$$

$$V_{or} = V_{ot} + V_{og} \tag{5.1b}$$

where V_{of} is the free oil specific volume; V_{ot} is the residual oil specific volume which is trapped in the liquid saturated zone; V_{og} is the residual oil specific volume held against gravitational drainage in the unsaturated zone; and V_{or} is the total residual oil specific volume in the saturated and unsaturated zones. The following sections

cover the model formulation for each component of the total oil specific volume.

5.1.1 Free oil specific volume

The free oil specific volume is defined by

$$V_{of} = \int_{Z_1}^{Z_u} \phi S_{of} dz \qquad (5.2)$$

where S_{of} is the free oil saturation, that is, the fraction of pore space filled with free oil. To characterize the vertical distribution of free oil in terms of the fluid table elevations, we must first introduce the concept of *capillary pressure*, and define air-oil and oil-water capillary pressure heads by

$$h_{ao} = h_a - h_o \qquad (5.3a)$$

$$h_{ow} = h_o - h_w \qquad (5.3b)$$

where h_o and h_w are oil and water pressure heads (see eq. 5.1), and h_a is the pressure head of air, which we assume is maintained at zero gauge pressure (that is, atmospheric). From the equilibrium pressure distributions given by (4.3), the vertical capillary head distributions are given by

$$h_{ao} = \rho_{ro}(Z - Z_{ao}) \qquad (5.4a)$$

$$h_{ow} = (1 - \rho_{ro})(Z - Z_{ow}) \qquad (5.4b)$$

Three phase saturation-capillary pressure relations are described by an extension of the van Genuchten model (*Parker et al.*, 1987; *Parker and Lenhard*, 1989) which gives the free oil saturation as

$$S_{of} = (1 - S_m)\left(1 + (\alpha\beta_{ao}h_{ao})^n\right)^{-m} + S_m - S_w \qquad h_{ao} > 0 \quad (5.5a)$$

$$S_{of} = 1 - S_w \qquad h_{ao} \le 0 \qquad (5.5b)$$

where S_w is the water saturation given by

$$S_w = (1 - S_m)\left(1 + (\alpha\beta_{ow}h_{ow})^n\right)^{-m} + S_m \qquad h_{ow} > 0 \qquad (5.6a)$$

$$S_w = 1 \qquad h_{ow} \le 0 \qquad (5.6b)$$

and S_m is the minimum water saturation under field conditions ("field capacity"), α [L^{-1}] and n [L°] are van Genuchten parameters for the soil, and $m = 1 - 1/n$.

The uppermost elevation in the soil where free oil exists, Z_x, we may determine by setting $S_{of} = 0$ in (5.5) and substituting the vertical capillary pressure distributions from (5.4) to obtain

$$Z_x = Z_{ow} + \frac{\rho_{ro}\beta_{ao}H_o}{\rho_{ro}\beta_{ao} - (1 - \rho_{ro})\beta_{ow}} \qquad (5.7)$$

where $H_o = Z_{ao} - Z_{ow}$. ARMOS assumes the soil surface elevation above Z_x. Thus, we may substitute Z_x for Z_u in (5.2). From (5.4) - (5.6), it is evident that free oil saturation is zero below Z_{ow}, so we may substitute Z_{ow} in place of Z_l in (5.2). Subtracting Z_{ow} from both the upper and lower bounds of integration indicates that V_{of} is a function of H_o only, independent of the absolute magnitudes of Z_{ao} and Z_{ow}.

Integration of the $V_{of}(H_o)$ function cannot be performed analytically. ARMOS determines V_{of} for discrete values of H_o once for each soil type by numerically integrating (5.2) using (5.4) - (5.6). The program stores the tabulated $V_{of}(H_o)$ values in an array for subsequent use by the numerical model, using a table look-up with piecewise linear interpolation. For illustrative purposes, we consider the behavior of a system with soil and fluid properties given in Table 1, typical of a medium sand with a light fuel oil. Figure 1 shows the relationship between V_{of} and H_o for this illustrative case.

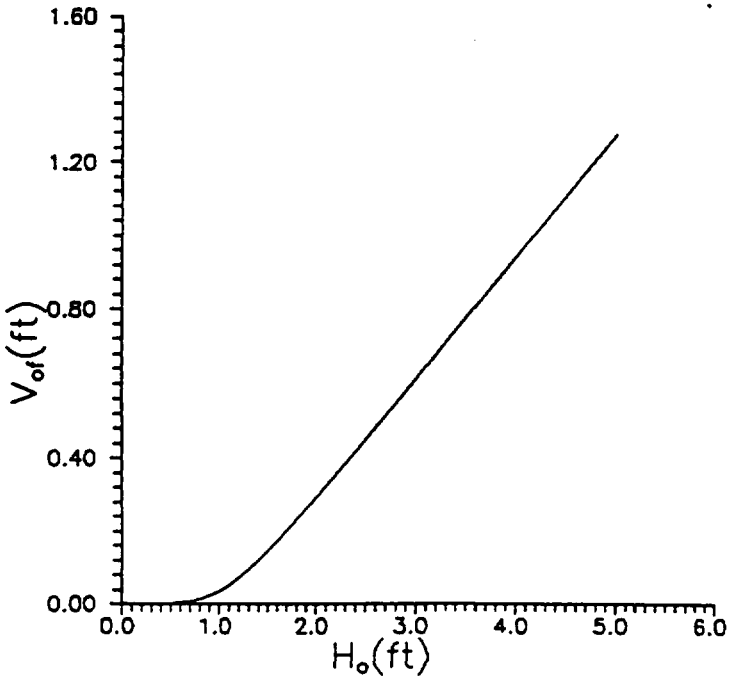
It is important to note that because we employ a general capillary pressure function, rather than a step-function curve used in some simplified models, the applicability of the model is not limited to coarse grained soils. Field studies have indicated that the three

phase van Genuchten model of *Parker et al.* (1987) provides a good representation for both coarse and fine grained soils (*Huntley and Hawk*, 1992; *Ostendorf et al.*, 1993).

Table 1. Soil and fluid properties for illustrations.

ρ_{ro}	= 0.8	K_{sw}	= 5.0 ft/day	S_m	= 0.25
η_{ro}	= 1.3	ϕ	= 0.35	S_{og}	= 0.05
β_{ao}	= 3.0	α	= 3.0 1/ft	S_{or}	= 0.20
β_{ow}	= 1.5	n	= 2.0		

Figure 1



Relationship between free oil specific volume and apparent oil thickness.

5.1.2 Saturated zone residual oil

The trapped oil specific volume, which occurs predominantly in the liquid saturated zone, is defined by

$$V_{ot} = \int_{z_l}^{z_u} \phi S_{ot} \, dz \tag{5.8}$$

where S_{ot} is the trapped oil saturation, which occurs as hydraulically discontinuous blobs occluded within the continuous water phase. Oil entrapment at a point in the soil occurs when water saturation increases. Due to heterogeneities at a scale smaller than the implicit averaging volume, displacement of oil by imbibing water is incomplete and isolated blobs of oil become cut off from the main body of free oil. (Previously free oil may thus become trapped.)

Since the oil-water capillary head controls water saturation, it is evident that changes in the oil-water capillary head will govern oil entrapment, and that these changes will control the trapped oil specific volume. At a given elevation, we may estimate the *trapped oil saturation*, S_{ot}, using an empirical relationship given by *Land* (1968) as

$$S_{ot} = (1 - S_m) \left\{ \frac{1 - \bar{S}_w^{min}}{1 + R_{ow}\left(1 - \bar{S}_w^{min}\right)} - \frac{1 - \tilde{S}_w}{1 + R_{ow}(1 - \tilde{S}_w)} \right\} \tag{5.9a}$$

where $\tilde{S}_w$ is the *apparent water saturation* and,

$$R_{ow} = \frac{1 - S_m}{S_{or}} - 1 \tag{5.9b}$$

$$\bar{S}_w^{min} = \frac{S_w^{min} - S_m}{1 - S_m}, \tag{5.9c}$$

in which S_{or} is the maximum residual oil saturation and S_w^{min} is the historical minimum water saturation that has occurred at a given elevation since the appearance of oil. If we flood a water-saturated core with oil and subsequently with water, the final oil saturation would correspond to S_{or}. We compute the apparent water saturation from

$$\tilde{S}_w = \left(1 + (\alpha\beta_{ow} h_{ow})^n\right)^{-m} \qquad h_{ow} > 0 \tag{5.10a}$$

$$\tilde{S}_w = 1 \qquad h_{ow} \le 0. \tag{5.10b}$$

The current water saturation at a given elevation may be computed from the current effective trapped oil $\bar{S}_{ot} = S_{ot}/(1-S_m)$ and apparent water saturations as

$$S_w = (1-S_m)(\tilde{S}_w - \bar{S}_{ot}) + S_m \qquad (5.11)$$

which may be compared with the historical values to determine S_w^{min}. In practice, an additional constraint placed on the trapped saturation is that the change in S_{ot} over a given time interval should not exceed the free oil saturation at the beginning of the interval. (In other words, oil must be present before it can be trapped!)

From (5.9) – (5.11) and expressions for free oil saturation given earlier, we may compute trapped oil saturation at an elevation subjected to a specific history of air-oil and oil-water capillary heads. Since we are interested in the vertically integrated behavior via (5.8), we wish to impose various paths for the air-oil and oil-water table elevations and determine the changes in trapped oil saturation as a function of elevation along the path. In other words, we assume a scenario involving temporal changes in Z_{ao} and Z_{ow}, compute the corresponding capillary heads and thus water, free oil and trapped oil saturations at specified elevations at each "time", and apply (5.8) to determine the trapped oil specific volume along the path. The results of such calculations indicate that the trapped oil specific volume is a function of the form

$$V_{ot} = f(\Delta Z_{ow}, H_o^{max}) \qquad (5.12)$$

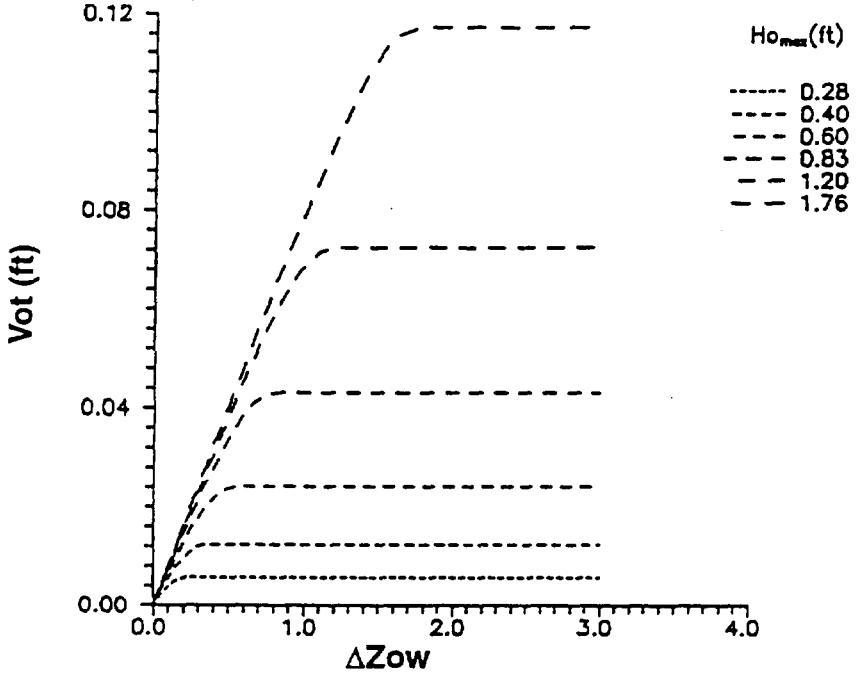
where $\Delta Z_{ow}=Z_{ow}-Z_{ow}^{min}$, in which Z_{ow} is the present oil water table elevation at a given areal location, Z_{ow}^{min} is the historical minimum oil-water table elevation since oil has reached the location, and H_o^{max} is the well oil thickness at the location before trapping begins. ARMOS computes (Z_{ow}^{min}, H_o^{max}) once for each soil type by numerically evaluating (5.8) for various imposed histories of Z_{ao} and Z_{ow}. It stores the tabulated functional values in an array for subsequent use by the numerical model as a table look-up using bilinear interpolation. The tabulated function is used to compute the *incremental* amount of trapped oil for the current time step using the current oil thickness for H_o^{max} and the incremental change in Z_{ow} for the time-step. If the oil-water table later drops, oil is "untrapped" in proportion to the ratio of the current oil-water table decrease to the differ-

ence between the current and historical maximum oil-water table. The maximum amount of trapped oil will occur if $\Delta Z_{ow} \ll H_o^{max}$ in which case

$$V_{ot} \rightarrow \phi S_{or} \Delta Z_{ow} \tag{5.13}$$

which has been empirically confirmed in the field by *Kemblowski and Chiang* (1990). Figure 2 shows the form of V_{ot} for the illustrative soil and fluid properties of Table 1.

Figure 2



Trapped oil specific volume versus ΔZ_{ow} and H_o^{max} .

5.1.3 Unsaturated Zone Residual Oil

In addition to the residual oil caused by fluid entrapment during water imbibition, another source of residual oil arises in the context of a vertically integrated model due to deviations from vertical equilibrium. During periods of falling Z_{ao}, downward oil redistribution eventually becomes negligible under gravitational forces when the oil saturation reaches a value which we term the "unsaturated

zone residual saturation." If we simulate vertical flow explicitly (for example, using the vertical multiphase flow model MOTRANS–ES&T, 1990), unsaturated zone residual saturation does not arise as a parameter, since it is essentially a correction for deviations from vertical equilibrium (e.g., *Kaluarachchi and Parker*, 1989), which can be predicted by the vertical flow model. However, in the context of a vertically integrated model like ARMOS, it is important to take this into account, particularly if large air-oil table changes occur.

The change in the unsaturated zone residual oil specific volume, V_{og}, for a time-step is computed by

$$\Delta V_{og} = \phi S'_{og} \Delta Z_{ao} \tag{5.14}$$

where ΔZ_{ao} is the change in the air-oil table for the time step, $S'_{og} = min(S_{og}, S_o^{max})$, in which S_{og} is the unsaturated zone residual saturation after drainage from a high oil content, and S_o^{max} is the current maximum oil saturation at the areal location corresponding to the current oil thickness H_o. If the air-oil table rises, residual oil is released from the unsaturated zone in a manner analogous to that in the saturated zone.

5.1.4 Capacity coefficients

To solve the oil flow equation, oil phase capacity coefficients, γ_{oo} and γ_{ow} must be specified. Having now fully described the functional relations for oil specific volume, we may proceed to determine the capacity coefficients. Expanding the definition of γ_{ow} given by (4.14) we obtain

$$\gamma_{ow} = \frac{\partial H_o}{\partial Z_{aw}} \frac{\partial V_{of}}{\partial H_o} + \frac{\partial Z_{ow}}{\partial Z_{aw}} \frac{\partial V_{ot}}{\partial Z_{ow}} + \frac{\partial Z_{ao}}{\partial Z_{aw}} \frac{\partial V_{og}}{\partial Z_{ao}} \tag{5.15}$$

To evaluate the first term, we note $\partial H_o / \partial Z_{aw} = -1/(1-\rho_{ro})$. Differentiation of the V_{of} versus H_o function is performed to obtain $\partial V_{of}/\partial H_o$ versus H_o which is stored in tabular form. To evaluate the second term in (5.15), we note that $\partial Z_{ow}/\partial Z_{aw} = 1/(1-\rho_{ro})$ and obtain $\partial V_{ot}/\partial Z_{ow}$ numerically. The last term in (5.15) is evaluated noting that $\partial Z_{ao}/\partial Z_{aw} = 1/\rho_{ro}$ and $\partial V_{og}/\partial Z_{ao}$ is evaluated from the unsaturated zone residual oil relation.

Proceeding in a similar fashion for γ_{oo} gives

$$\gamma_{oo} = \frac{\partial H_o}{\partial Z_{ao}} \frac{\partial V_{of}}{\partial H_o} + \frac{\partial Z_{ow}}{\partial Z_{ao}} \frac{\partial V_{ot}}{\partial Z_{ow}} + \frac{\partial V_{og}}{\partial Z_{ao}} \tag{5.16}$$

which is evaluated in a manner similar to that for the oil-water capacity coefficient. For the water flow equation, it may be easily found that

$$\phi_e = \phi (1 - S_m) \tag{5.17}$$

where ϕ_e is the drainable porosity (or specific yield).

5.2 Transmissivity Relations

Water transmissivity is computed from (4.9b), assuming water relative permeability can be approximated as a step function changing from one to zero at a specified elevation, normally assumed to be the current value of Z_{ow}. In certain cases, the current Z_{aw} is used in lieu of Z_{ow} to reduce the coupling between the oil and water flow equations, which can induce numerical difficulties in some problems. Thus,

$$T_{wij} = K_{sw_{ij}} (Z_{uw} - Z_l) \tag{5.18}$$

where Z_l is the (effective) lower elevation of the aquifer and Z_{uw} is the current air-water or oil-water table.

Horizontal anisotropy in ARMOS is parameterized by the mean saturated hydraulic conductivity, $\bar{K}_{sw} = \left(K_{sw}^{max} + K_{sw}^{min} \right) / 2$, the ratio of maximum to minimum conductivity, $R = K_{sw}^{max} / K_{sw}^{min}$, and the angle between the y-axis of the domain and the principal axis of the conductivity tensor, ω, measured positive clockwise. The conductivity tensor components in the x-y plane of the model are given by

$$K_{sw_{xx}} = \cos^2 \omega \frac{2\bar{K}_{sw}}{1+R} + \sin^2 \omega \frac{2R\bar{K}_{sw}}{1+R} \tag{5.19a}$$

$$K_{sw_{yy}} = \cos^2\omega \frac{2R\bar{K}_{sw}^{\,2}}{1+R} + \sin^2\omega \frac{2\bar{K}_{sw}^{\,2}}{1+R} \qquad (5.19b)$$

$$K_{sw_{xy}} = K_{sw_{yx}} = \frac{2\bar{K}_{sw}(R-1)}{1+R} \sin\omega \cos\omega \qquad (5.19c)$$

To evaluate oil transmissivity, an expression for oil conductivity as a function of elevation is needed to substitute in (5.9). The oil phase conductivity is assumed to be of the form

$$K_{oij} = \frac{k_{ro} K_{sw_{ij}}}{\eta_{ro}} \qquad (5.20)$$

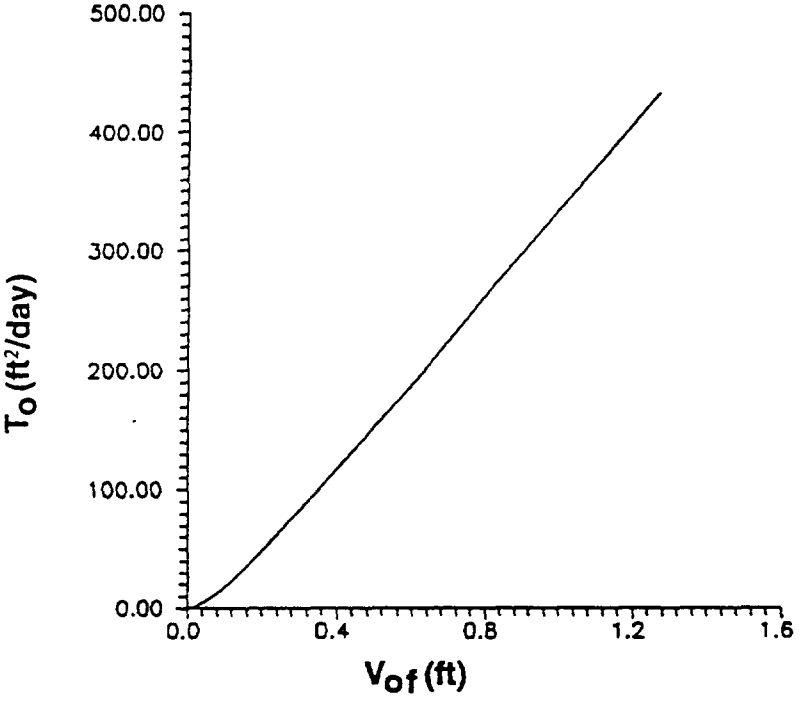
where k_{ro} is the relative permeability of oil, η_{ro} is the ratio of oil to water viscosity, and $K_{sw_{ij}}$ is the saturated conductivity for water. ARMOS calculates the oil relative permeability based on the *van Genuchten* (1980) model, with a refinement to account for permeability reduction due to immobile oil following the approach of *Kaluarachchi et al.* (1992). The oil permeability expressions may be written as

$$k_{ro} = \left(\bar{S}_t - S_w\right)^{1/2}\left(\left(1 - S_w^{\,1/m}\right)^m - \left(1 - \bar{S}_t^{\,1/m}\right)^m\right)^2 \qquad (5.21)$$

where $\bar{S}_t = (S_w + S_o)/(1 - S_m)$. Upon integrating (4.9b) with (5.20), (5.21) (5.10) and (5.11), it is found that oil transmissivity varies almost linearly with the free oil specific volume.

ARMOS computes the $T_o(V_{of})$ relation for each soil by numerical integration for a series of monotonically increasing H_o with decreasing Z_{ow} and increasing Z_{ao} so that the residual oil specific volume remains zero. The resulting function is stored for table look-up using piecewise linear interpolation. Figure 3 shows a representative $T_o(V_{of})$ function.

Figure 3.



Relationship between oil transmissivity T_o and free oil specific volume V_{of} for illustrative system.

5.3 Estimation of Fluid Properties

5.3.1 Product specific gravity

Oil specific gravity, ρ_{ro}, varies significantly for different petroleum hydrocarbons depending on their chemical composition. Typical values for various products at 15°C are given in Table 3. Specific gravity increases with decreasing temperature by about 0.0005 - 0.0015 per degree celsius. We recommend direct measurement of specific gravity, since such determinations are very simple and inexpensive to perform using standard methods (e.g., ASTM D-1298, D-1217). Measurements may be performed in the laboratory on product samples using standard methods for fluid density determination. Since hydrocarbon density varies with temperature, mea-

surements should be made at a temperature close to that expected in the field.

A simple field procedure to determine product density in wells with free product is to measure the water piezometric elevation (Z_{aw}) using a tube inserted through the oil layer in the monitoring well, and to measure the air-oil and oil-water table elevations under static conditions. We compute the product density by

$$\rho_{ro} = \frac{Z_{aw} - Z_{ow}}{Z_{ao} - Z_{ow}}. \qquad (5.22)$$

Since (5.22) assumes that equilibrium conditions exist within the well bore, it is advisable to wait until fluid levels are stable after inserting piezometer tubes before taking readings.

Table 2 Fluid and soil properties used by ARMOS.

Fluid properties:	
ρ_{ro}	Ratio of oil to water density [L^o]
η_{ro}	Ratio of oil to water viscosity [L^o]
β_{ao}	Ratio of water surface tension to oil surface tension [L^o]
β_{ow}	Ratio of water surface tension to oil-water interfacial tension [L^o]
Soil properties:	
K_{sw}	Saturated hydraulic conductivity, average of anisotropic components [$L\,T^{-1}$]
R	Ratio of maximum and minimum hydraulic conductivity components
ω	Angle of principal component of conductivity from north
ϕ	Total porosity [L^o]
S_m	Water saturation at field capacity [L^o]
S_{og}	Maximum unsaturated zone residual oil saturation [L^o]
S_{or}	Maximum saturated zone residual oil saturation [L^o]
α	VG mean pore size parameter [L^{-1}]
n	VG pore size distribution exponent [L^o]

Table 3 Typical specific gravity (ρ_{ro}), oil-water viscosity ratio (η_{ro}), and capillary scaling factors (β_{ao} and β_{ow}) for various hydrocarbon mixtures. Values in parentheses are estimates.

Product	ρ_{ro}	η_{ro}	β_{ao}	β_{ow}
Gasoline	0.73	0.62	3.3	1.4
Diesel fuel	0.83	2.7	2.8	1.4
Kerosene	0.84	2.3	2.6	1.5
Fuel oil #2	0.87	5.3	2.8	1.4
Fuel oil #4	0.90	47	(2.8)	(1.4)
Fuel oil #5	0.92	215	(2.8)	(1.4)
Fuel oil #6	0.97	6350	(2.8)	(1.4)

5.3.2 Product viscosity

Dynamic (also called "intrinsic") viscosity can be measured using standard methods (e.g., ASTM D-88, D-4243, D-871, D-1795). For refined petroleum hydrocarbons, we have found the following approximate correlation between specific gravity and viscosity at 20°C

$$\eta_{ro} = 8.28\rho_{ro}^{9.5} \tag{5.23}$$

where η_{ro} is the ratio of dynamic viscosity of product to that of water. Typical values for various products are given in Table 4 at 15°C (*API*, 1989). Viscosity increases with decreasing temperature by about 1-2 percent per degree celsius.

5.3.3 Fluid scaling factors

Air-oil and oil-water scaling factors (β_{ao} and β_{ow}) are necessary to describe three phase saturation-capillary pressure relations. One may estimate the scaling factors from oil surface tension and oil-water interfacial tension data (*Lenhard and Parker*, 1987) as

$$\beta_{ao} = \sigma_w/\sigma_o \tag{5.24a}$$

$$\beta_{ow} = \sigma_w/\sigma_{ow} \tag{5.25a}$$

Estimation of scaling factors from surface and interfacial tension data

where σ_w is the surface tension of water (ca. 72 dynes/cm), σ_o is the surface tension of the organic liquid, and σ_{ow} is the oil-water interfacial tension. An alternative protocol for determining β_{ow} is to measure the surface tension of water saturated with dissolved hydrocarbon (in other words, water which has been shaken with hydrocarbon and decanted to remove all traces of free liquid), and to estimate the interfacial tension via

$$\sigma_{ow} = \sigma'_w - \sigma_o \tag{5.26}$$

where σ'_w is the surface tension of water saturated with dissolved hydrocarbon. In the absence of measurements of either σ_{ow} or σ'_w, we may obtain an estimate of β_{ow} assuming $\sigma'_w \approx \sigma_w$, which indicates that

$$\beta_{ow} \approx \frac{1}{1 - 1/\beta_{ao}}. \tag{5.27}$$

Surface and interfacial tension may be determined in the laboratory using standard methods (e.g., ASTM D-971). Table 4 gives estimates of β_{ao} and β_{ow} based on (5.24) with surface tension and interfacial tension data at 20°C from *Mercer and Cohen* (1990).

Estimation of scaling factors for crude oil

For unrefined petroleum hydrocarbons (that is, crude oil), one may obtain an estimate of the scaling factors using a correlation between oil surface tension and specific gravity given by *Baker* and *Swerdloff* (1956) as

$$\beta_{ao} = \frac{1}{1 - 1/2\rho_{ro}} \tag{5.28a}$$

$$\beta_{ow} = 2\rho_{ro} \tag{5.28b}$$

which provides a simple procedure for estimating scaling factors for unrefined hydrocarbons in the absence of additional information. *Lyman et al.* (1982) reviewed procedures for estimation of surface tension and interfacial tensions of fluid mixtures.

5.4 Estimation of Soil Properties

5.4.1 General methodology

Soil properties required to describe oil and water retention and movement include parameters defining the fluid retention properties and soil permeability. If properties exhibit variations in the vertical direction, we employ parameters relevant to the capillary fringe zone (where most oil occurs) to predict oil recovery with maximum accuracy. If this results in an under- (or over-) estimate of the water transmissivity, one may correct it by adjusting the effective and actual aquifer lower boundaries deeper (or shallower) in proportion to the error in the aquifer conductivity.

Pump tests or slug tests are the preferred method to obtain saturated hydraulic conductivity, although laboratory tests may be sufficiently accurate if sample disturbance is minimal and enough samples are obtained to compute a representative average. When averaging multiple determinations of hydraulic conductivity or other soil parameters, we recommend employing a geometric average as

$$G = exp\left\{\frac{\Sigma ln\, X_i}{N}\right\} \qquad (5.29)$$

where X_i are the measurements (i = 1,...,N) and G is the geometric average.

5.4.2 Total porosity, effective porosity and field capacity

We may determine total porosity, ϕ, directly from soil cores, or indirectly from neutron logging or other in situ methods. The parameter S_m represents the minimum water saturation that will occur in the soil under field conditions. Note that the minimum sat-

uration determined by fitting to laboratory moisture retention data is usually smaller than the minimum field water content, because equilibrium conditions do not occur in the field. We may estimate S_m from direct measurements of the degree of saturation on soil cores taken from the field at elevations above the "capillary fringe" where water saturation drops more or less sharply.

If the specific yield of the unconfined aquifer is known, this may be used to estimate S_m as

$$S_m = 1 - \phi_e / \phi \tag{5.30}$$

where ϕ is the total porosity of the soil and ϕ_e is the specific yield. Measured specific yields often increase with the duration of pump tests due to "delayed yield" effects. Since long term drainage is of concern here (mostly weeks to months), specific yields from short term pump tests may lead to overestimation of S_m.

If laboratory moisture retention data are available, we may make an estimate of S_m by evaluating the water saturation at an air-water capillary pressure head of ca. 100 to 300 cm, which is commonly regarded as an approximation of "field capacity."

Table 4 Representative quasi-static soil properties for various soils (USDA size classification).

Soil type *	K_{sw} (ft/d)	α (1/ft)	n	S_m	S_{or}	S_{og}
Sand	23.3	4.5	2.7	0.13	0.26	.03
Loamy sand	11.5	3.8	2.4	0.21	0.24	.05
Sandy loam	3.48	2.3	2.0	0.24	0.23	.05
Sandy clay loam	1.02	1.8	1.5	0.28	0.22	.06
Loam	0.82	1.1	1.7	0.35	0.19	.07
Silty loam	0.36	0.67	1.7	0.43	0.17	.07
Clay loam	0.20	0.64	1.7	0.55	0.13	.07
Sandy clay	0.095	0.97	1.8	0.66	0.10	.07
Silty clay loam	0.056	0.37	1.9	0.68	0.10	.06
Silty clay	0.016	0.26	2.8	0.84	0.05	.04

5.4.3 Residual oil saturations

Maximum residual oil saturations in the unsaturated and saturated zones are needed to estimate recoverable product. One may determine the maximum unsaturated zone residual oil saturation, S_{og}, in the laboratory by measuring the oil saturation in a soil core taken at a location where oil has been able to drain from a previous oil imbibition event for at least several days. Note that water and oil will not drain from a short column in the laboratory as it does in the field because the capillary pressure at the column boundary is zero. Typical values of S_{or} for field soils are in the range given by

$$S_{og} \approx f_{og} S_m (1 - S_m) \tag{5.31}$$

where f_{og} may range from 0.2 to 0.5 with a median of around 0.3. Fluids with higher viscosities and soils that are more heterogeneous will tend to have larger f_{og} values. Theoretical analyses indicate that residual saturation increases approximately proportional to the fourth root of product viscosity (i.e., $f_{og} \alpha \eta_{ro}^{1/4}$, where η_{ro} is the oil-water viscosity ratio).

One may determine the saturated zone residual oil saturation, S_{or}, by measuring the final oil saturation in an initially water saturated soil core subjected to oil flooding followed by water flooding. Typical values of S_{og} are given by

$$S_{or} \approx f_{or} (1 - S_m) \tag{5.32}$$

where f_{or} ranges from 0.2 to 0.5 with a median of about 0.3. Fluids with higher viscosities, and soils that are more heterogeneous, tend to have larger f_{or} values.

5.4.4 Capillary pressure parameters from soil cores

Air-water capillary pressure curves are often characterized by fitting model parameters (i.e., α, n and S_m) to water content versus capillary pressure data obtained in the laboratory on soil cores (which yield *true equilibrium* parameters). However, in the field, equilibrium is never truly attained since low relative permeabilities impede fluid drainage as wetting phase saturations diminish. To

correct for the deviation from equilibrium conditions, we use *quasi-static* model parameters, which yield the correct water saturation distribution under field conditions when assuming a hydrostatic water pressure distribution. *Lenhard and Parker* (1990) describe procedures to estimate *quasi-static* retention parameters from laboratory data. The simplest approach is to fix S_m at a value corresponding to the minimum field water saturation, discard moisture data below about $S_w \approx 1.1 \times S_m$, then fit the parameters α and n to the reduced data set using a nonlinear regression method. Table 5.3 gives typical quasi-static van Genuchten (VG) model parameters for various soil types computed from equilibrium values reported by *Carsel and Parish* (1988).

5.4.5 Capillary pressure parameters from grain size data

Arya and Paris (1981) derived a theoretical procedure to estimate air-water capillary pressure parameters (that is, α, n and S_m) based on the proposition that capillary pressure relations relate to the pore size distribution of the soil, which we may in turn infer from the grain size distribution. *Mishra et al.* (1988) calibrated and implemented the method in the program SOILPROP (*ES&T*, 1990), which ARMOS incorporates. We may either specify S_m as known (computed, for example, from specific yield –see Section 5.4.2), or the program estimates S_m to correspond to "field capacity" for the soil defined operationally as the water saturation at which the air-water capillary head is 100 cm.

5.4.6 Capillary pressure parameters from saturated conductivity correlation

Another method to estimate the VG parameter α is to employ a correlation with saturated hydraulic conductivity as

$$\alpha \approx A K_{sw}^{1/2} \tag{5.33}$$

Based on laboratory analyses of vertical conductivity, $A \approx 1.5\, d^{1/2} ft^{-3/2}$ (±50%). Since field-measured horizontal conductivities (for example, from slug or pump tests) are generally much higher than vertical laboratory values, α may be overestimated using this value of A with field measured conductivities

5.4.7 Capillary pressure parameters from TPH data

The most critical soil parameter in estimating oil saturation distributions and spill volume is typically the capillary curve parameter α. If independent data are available on oil saturation at points in the field, under certain conditions it may be possible to use these to calibrate the value of α. Since oil saturation and soil total petroleum hydrocarbon (TPH) are related, an algorithm was developed to calibrate α [L^{-1}] from TPH and monitoring well data. The method is based on the premise that oil saturation distributions computed for given well fluid levels from the three phase saturation relations discussed in Section 5.1, should agree with TPH data, if fluid levels at the time soil samples are taken are known and if one properly calibrates the capillary model. The method requires as input well product thicknesses H_o, and oil-water table elevations Z_{ow} in monitoring wells at specified coordinates (x_w, y_w); TPH measurements from a given depth interval for specified coordinates (x_T, y_T); as well as estimates of total porosity ϕ, irreducible water saturation S_m, the van Genuchten parameter n, oil specific gravity ρ_{ro}, and fluid-dependent scaling factors β_{ao} and β_{ow}.

The major steps of the algorithm are as follows: (i) interpolate Z_{ow} and H_o at locations (x_T, y_T), where TPH is measured onto a regular computational grid, (ii) at each soil bore location, calculate an average free oil saturation $\bar{S}_{of}$ from the interpolated fluid levels over the interval of TPH measurements, and use this $\bar{S}_{of}$ to calculate a corresponding TPH value, (iii) compare measured and calculated TPH values and iteratively adjust the value of α to minimize the sums of squared deviations.

Free oil saturation S_{of} at a given location (x_T, y_T) and elevation Z, is computed using (5.4) to (5.6), and $\bar{S}_o$ is determined by averaging S_o computed at midpoints, lower and upper limits for TPH measurement intervals. TPH (in mg/kg) is calculated from S_o as

$$TPH = \frac{\rho_o \bar{S}_o \phi}{\rho_b} \times 10^6 \qquad (5.34)$$

where ρ_o is the oil density and ρ_b is the soil bulk density. For step (iii), ARMOS uses measured TPH data only for intervals within elevations where free oil saturation should be non-zero. A lower limit Z_l and an upper limit Z_u defines this interval. ARMOS eliminates TPH data from the regression analysis if $Z_l < Z_{ow}$ or $Z_u > Z$ where Z is defined by (5.7).

The applicability of this method is critically dependent on accurately defining the fluid levels at the time TPH samples are taken. If well product thickness is large (several feet) the method will be most reliable because uncertainty in fluid levels will have less effect on TPH predictions. The difficulty of making accurate measurements of TPH in the zone of free product should be carefully considered when employing this method.

6. Model Verification and Model Applications

6.1 Overview

In this chapter, we present comparisons of ARMOS results with analytical and other numerical solutions for various problems to verify the accuracy of the water and oil flow solutions. A representative hypothetical field scale application is presented to illustrate the use of the model to evaluate remedial design options. Finally, an actual field application to a pipeline leak site is presented that illustrates practical model calibration procedures.

Application of the model to the pipeline leak site indicated it is capable of describing product recovery and well product level fluctuations in the field, even under conditions of fluctuating water tables. Soil parameters estimated from grain size distribution data yielded estimated recovery 30% below the measured recovery. Calibration using skimming data for a 100 day period reduced the error in estimated recovery to 20%. The sharp reduction in product recovery rates associated with a rising water table were predicted closely by the model, even using initial parameters estimates from grain size data.

The results indicate that ARMOS is capable of accurately solving complex field problems with modest computational resources. Simulation of product recovery for a 200 day period in the example optimation problem took only 8 minutes on a 50 Mhz 80486 computer. Product recovery for the pipeline leak problem over a 950 day period was simulated in 96 minutes on similar hardware. Final mass balance errors for the problems ranged from 0.04 to 0.8 percent.

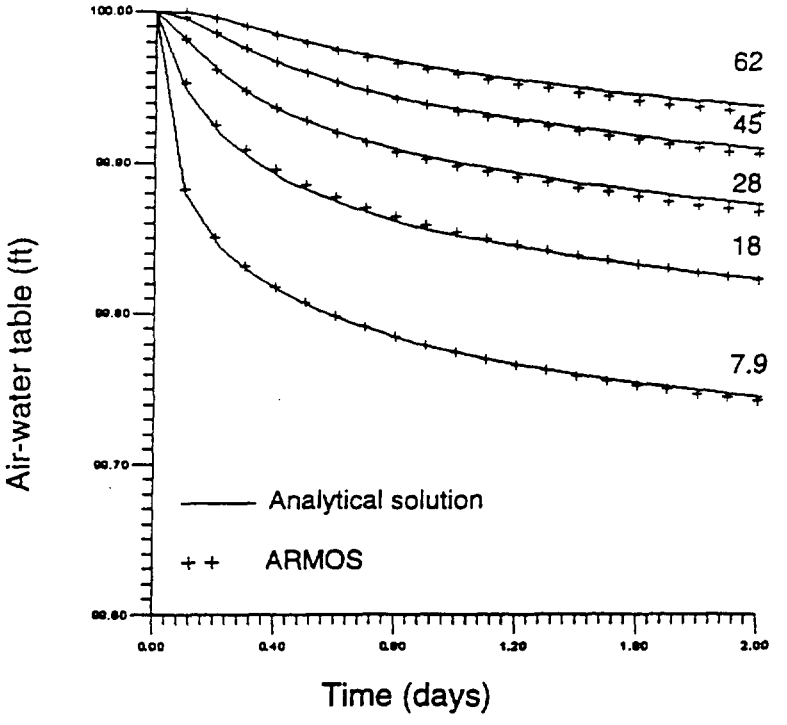
6.2 Water Flow Model Verification

6.2.1 Comparison with analytical solutions

The single phase water flow solution in ARMOS was tested by comparing numerical model results with the Theis analytical solution for transient pumping from a single well (*Freeze and Cherry*, 1979). Although the Theis solution is strictly valid for confined aquifers, the solution is accurate for unconfined flow if the drawdown is small relative to the aquifer thickness, as will be the case for this example. The problem assumes an unconfined aquifer with a bottom elevation at Z=0 and an initial level water table elevation at Z=100 feet. The isotropic hydraulic conductivity of the aquifer (K_{sw}) is 10 feet/day, the porosity (ϕ) is 0.35, and the field capacity water saturation (S_m) is 0.1, corresponding to a specific yield ($\phi_e=\phi(1-S_m)$) of 0.315. The domain for the numerical problem is 500 X 500 feet with a well at the center. The grid spacing for ARMOS is 6 feet at the well and increases to 10 feet at the outer perimeter. The boundary condition on the outer perimeter of the numerical model is a prescribed head held constant at the initial level. The well is fully penetrating and is pumped at a constant rate of 600 ft^3 per day. Since the analytical solution assumes an infinite areal domain, it is valid for a finite domain only up to the time when drawdown is propagated to the finite boundary. For the example problem, this time is computed from the analytical solution to occur at about 2 days. Hence, the solutions are compared for times less than this.

Single phase water flow. A comparison of the Theis solution and the numerical solution obtained from ARMOS at observation wells located 7.9, 18, 28, 45 and 62 feet from the pumping well is shown in Figure 1. The agreement is very close, indicating that the solution algorithm for transient water flow is implemented correctly in ARMOS and that the solution is accurate.

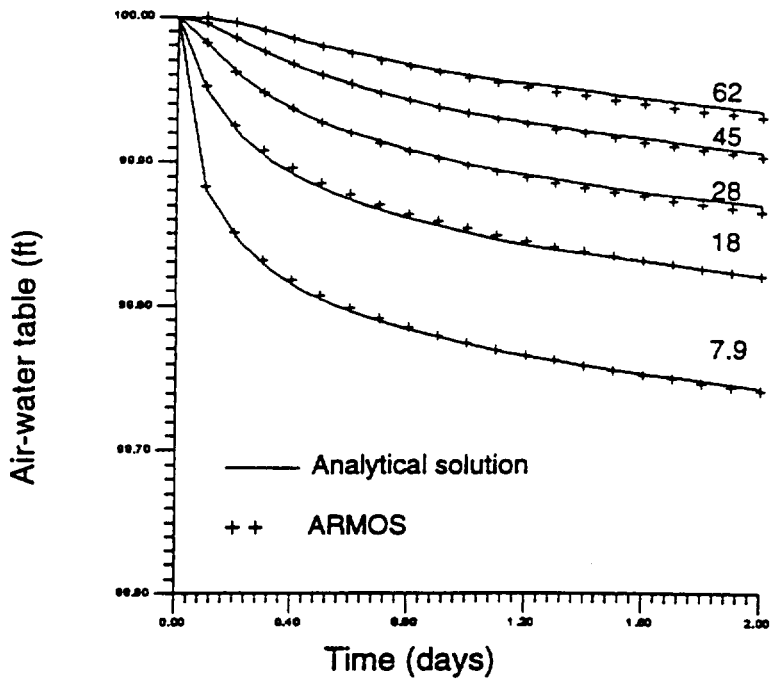
Figure 1



Water table elevation versus time computed by ARMOS and Theis solution. Radial distance to observation points in feet shown on curves.

Effects of oil on water flow solution. In addition to the option to solve for water flow only, ARMOS can also solve for simultaneous flow of water and oil. Since the water flow solution is only weakly coupled to the oil flow solution, the water flow solution in ARMOS when both flow equations are solved should give nearly identical results for the air-water table to the single phase solution. The identical water pumping problem described above was solved with ARMOS, except that in addition to pumping water, oil recovery was also modeled at the pumping well. An initial uniform oil thickness of 1 foot was assumed, and oil was skimmed at the pumping well to maintain well oil thickness at zero. Water drawdown versus time at observation wells 7.9, 18, 28, 45 and 62 feet from the recovery well computed by ARMOS is compared to the Theis solution result in Figure 2. The results differ imperceptibly, verifying the accuracy of the water flow solution in ARMOS when solving for oil and water flow.

Figure 2



Air-water table elevation versus time during two-phase flow computed by ARMOS and Theis solution. Radial distance to observation points in feet shown on curves.

6.2.2 Comparison with SUTRA

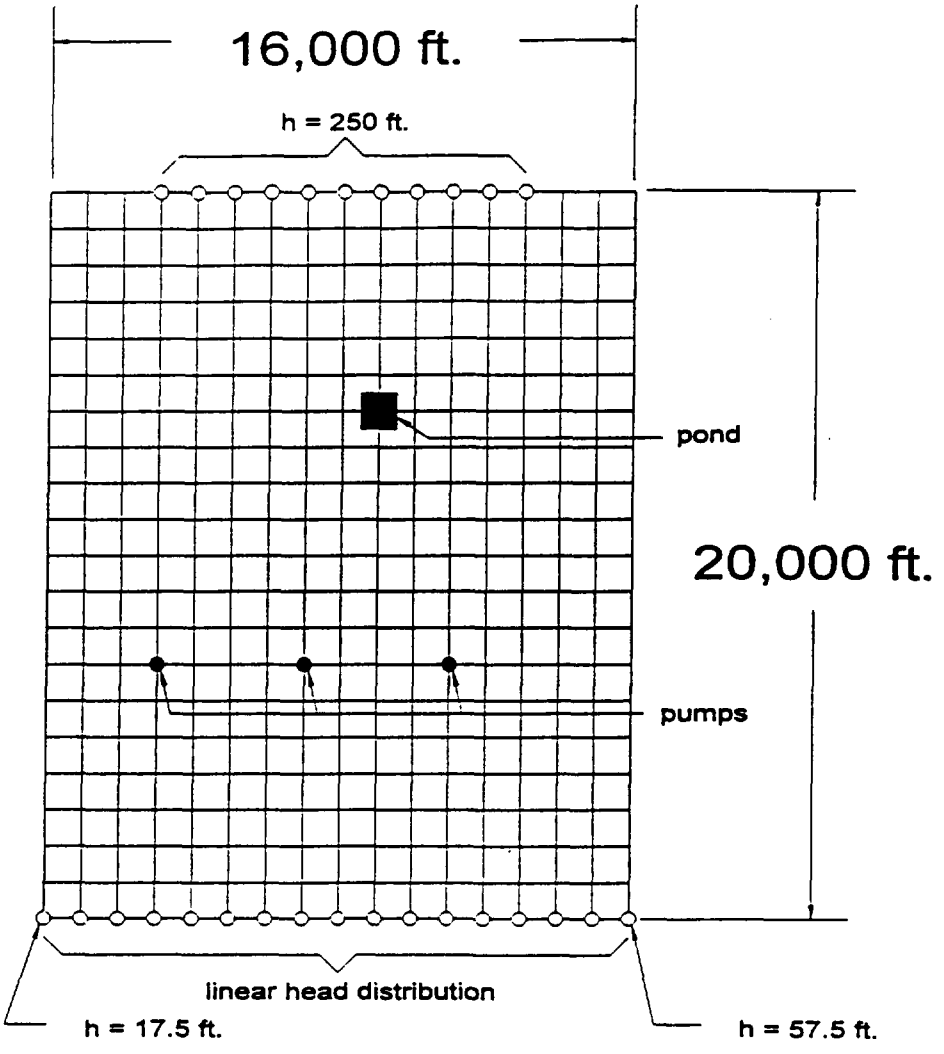
SUTRA is a two-dimensional finite element model developed by the U.S. Geological Survey (*Voss*, 1984), designed to simulate saturated-unsaturated flow in vertical cross-sections or saturated areal confined groundwater flow. We compared the water flow solution of ARMOS with the areal flow results from SUTRA for various scenarios involving steady-state and transient flow with or without pumping and injection for an anisotropic, unconfined aquifer.

Following *Voss* (1984), the example problem involves a 16,000 X 20,000 foot model domain (Figure 3). A rectangular mesh was created with 357 nodes and 320 elements, each 1,000 X 1,000 feet. The center 11 nodes along the top (north) boundary are specified as having a constant head of 250 feet. All nodes along the southern bottom boundary are specified as constant head, with the southwest

corner at 17.5 feet and the southeast corner at 57.5 feet. A linear head distribution was assumed between the southwest and southeast corners. Boundary nodes along the eastern and western sides of the domain are treated as no-flow. Aquifer materials are homogeneous and anisotropic, with a maximum hydraulic conductivity of 100 ft/day and minimum conductivity of 21.6 feet/day. The angle between the principle axis of the conductivity tensor, clockwise from north is 60 degrees. This is equivalent to $\overline{K}_{sw}$ = 60.8 feet/day, R = 4.63, and ω = 60 degrees for ARMOS. The aquifer specific yield was assumed to be 0.2, which is parameterized by ARMOS using a total porosity of 0.2 (ϕ) and a field capacity water saturation (S_m) of zero. The aquifer is assumed to have a uniform initial thickness of 400 feet. SUTRA assumes aquifer thickness is independent of water head (confined flow), while ARMOS considers unconfined flow. Effects of these differences will be discussed below.

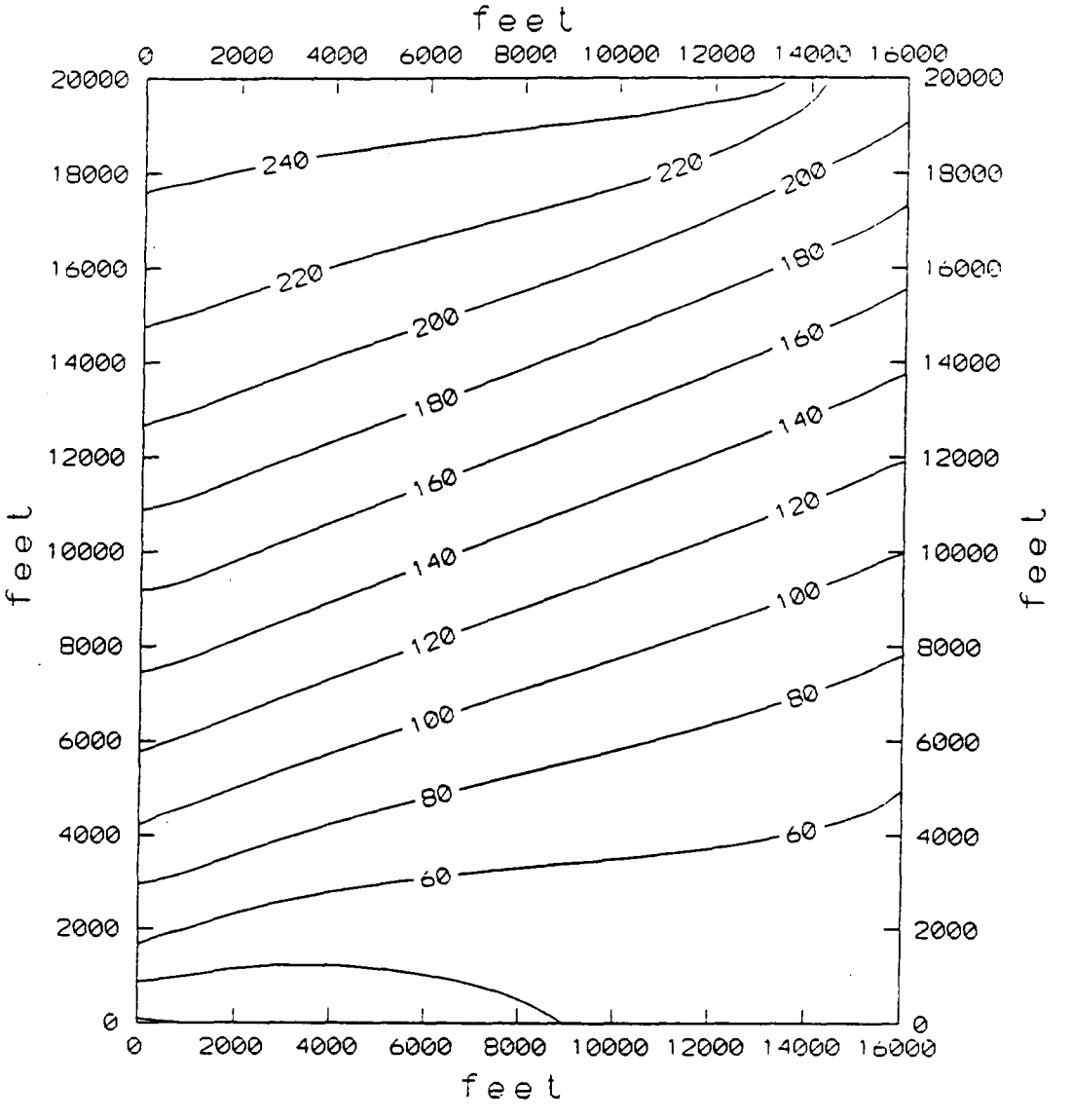
Steady-state flow with no pumping. We first ran ARMOS and SUTRA to determine the steady-state head distributions assuming no sources or sinks. To overcome SUTRA's inability to model unconfined flow, we adjusted the aquifer bottom elevation in ARMOS so that the aquifer thickness at steady-state was exactly 400 feet, the same thickness used in SUTRA. The hydraulic heads for ARMOS and SUTRA are shown in Figures 4a and 4b, respectively. The results indicate essentially perfect agreement between the two models.

Figure 3



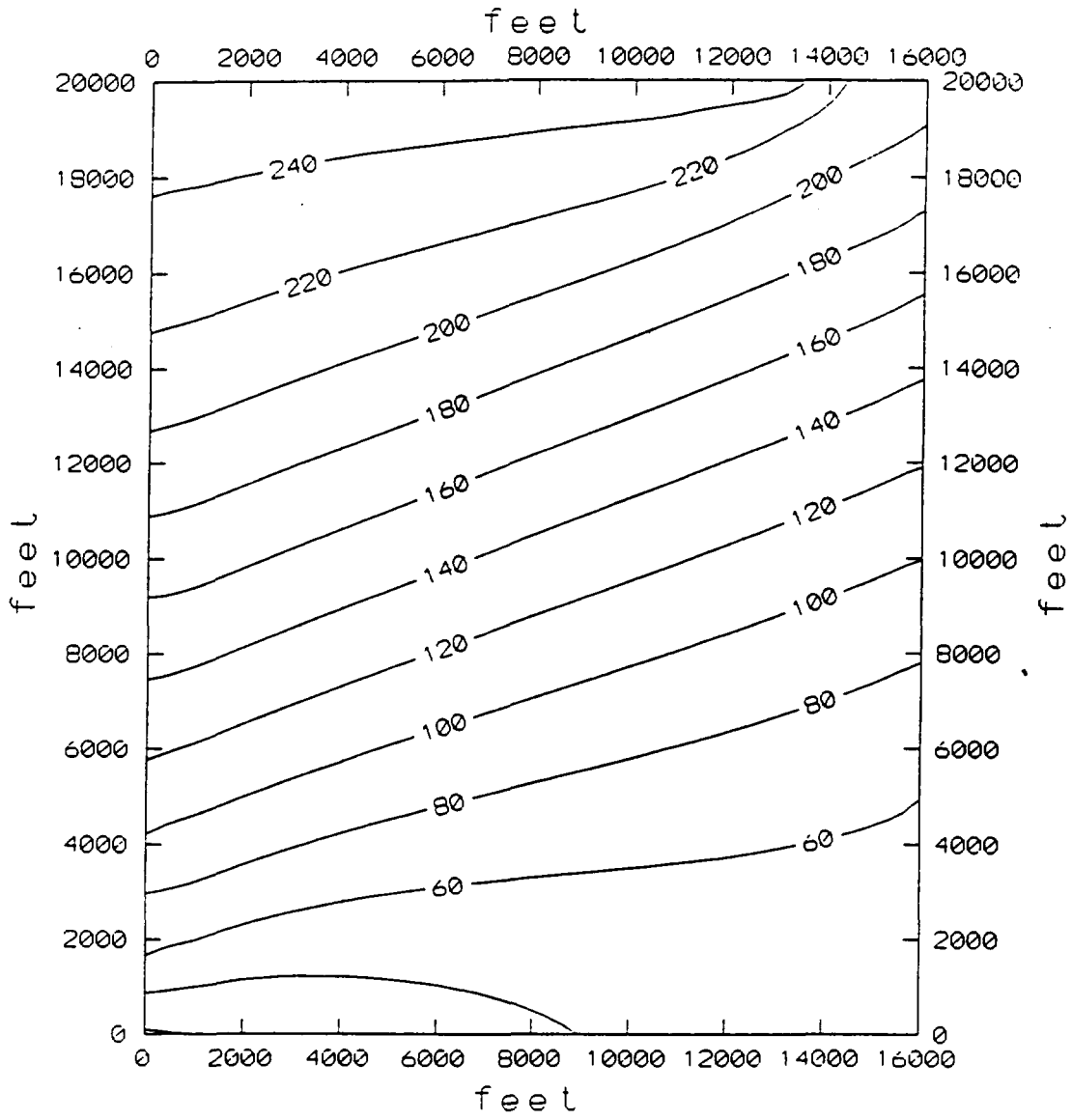
Model domain for ARMOS and SUTRA water flow simulations.

Figure 4a



Steady-state heads without pumping computed by ARMOS

Figure 4b



Steady-state heads without pumping computed by SUTRA.

Transient flow with pumping and recharge. A leaky pond at coordinates 9,000 east and 15,000 north (assuming the southwest corner is survey origin) was modeled as a node with constant water injection rate of 1.9×10^6 feet^3/day. Three fully penetrating pumping wells were also modeled located at coordinates 3,000 east, 7,000 north; 7,000 east, 7,000 north; and 11,000 east, 7,000 north. Each well had a constant water pumping rate of 1.73×10^6 feet^3/day. The initial condition for the problem was taken as the steady-state flow field with no sources or sinks (Figure 4). Transient flow simulations were performed for a 20 day period with constant pumping and recharge.

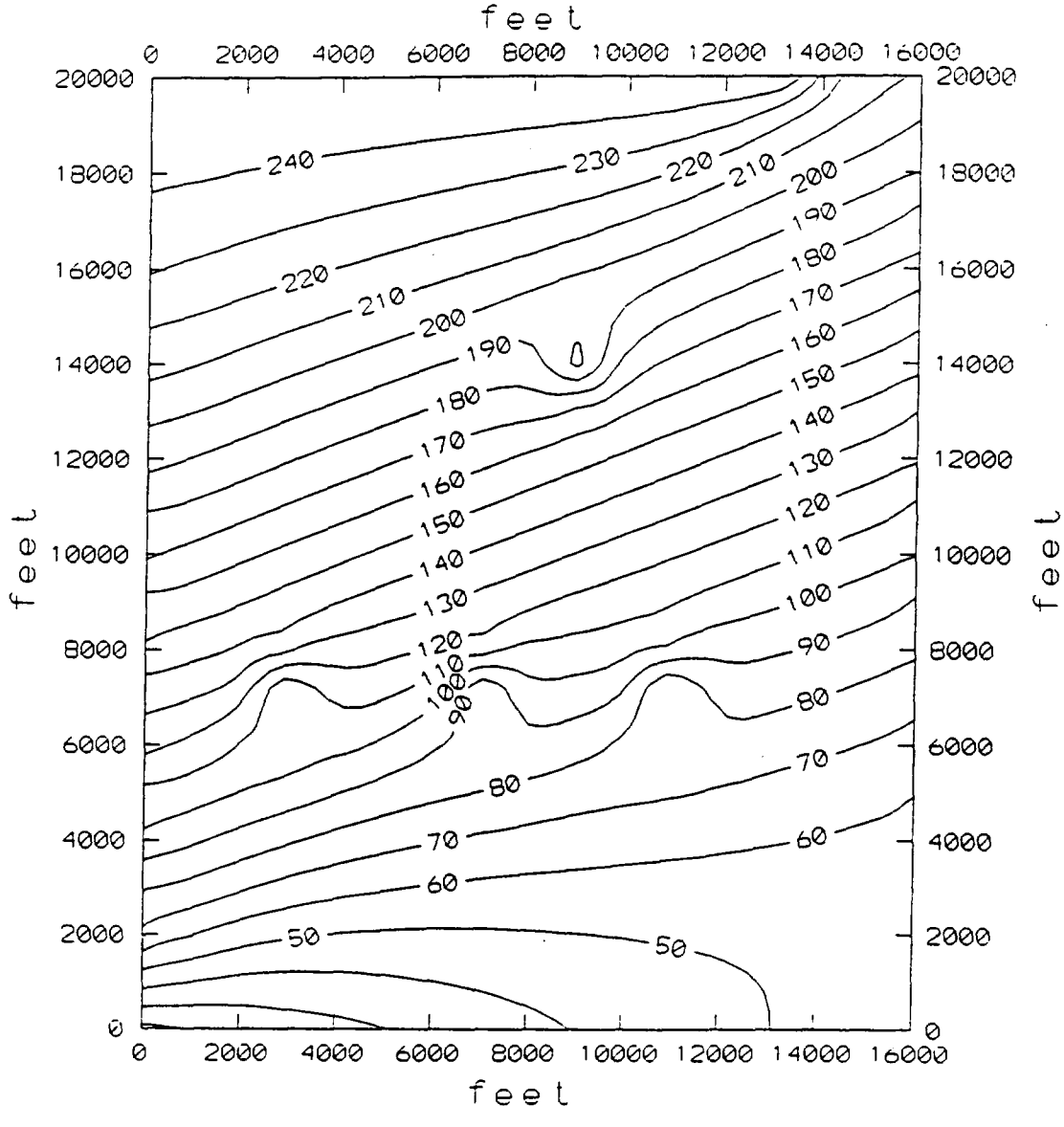
Hydraulic heads after 5, 10 and 20 days of pumping and recharge computed by ARMOS and SUTRA are shown in Figures 5 - 7. The results indicate close correspondence between the two models, although ARMOS predicts increasingly greater drawdown near wells as time progresses. This may be attributed to the fact that SUTRA assumes aquifer transmissivity is independent of head (confined flow), whereas ARMOS updates transmissivity as the water table elevation changes (unconfined flow). As drawdown increases with time due to pumping, the transmissivity near a well will diminish in an unconfined aquifer, requiring a greater drawdown to compensate for the lower transmissivity. Therefore, the results of ARMOS should be more accurate for unconfined aquifer flow.

Steady-state flow with pumping and recharge. To further investigate the effects of transmissivity variations with water table elevation, and to confirm the explanation for deviations between ARMOS and SUTRA transient flow results, additional steady-state simulations were performed using the same water pumping and injection conditions. First, ARMOS was run to steady-state for the same pumping and recharge conditions and using the same aquifer lower elevation (400 feet below the initial water level) used in the transient simulations. The results (Figure 8a) correspond to the steady-state water table elevation for the stressed unconfined aquifer. Second, ARMOS was run to steady-state using adjusted aquifer bottom elevations that correspond to a *final* aquifer thickness of 400 feet over the entire domain. The results represent the piezometric head at steady-state for a confined aquifer. The confined aquifer results (Figure 8b) indicates about 85 feet of drawdown at wells (initial elevation of ca. 100 feet minus final elevation ca. 15 feet); whereas, the unconfined case (Figure 8a) indicates about 95 feet of drawdown. Thus, drawdown is underpredicted by about 10 percent when the unconfined aquifer is approximated as confined, and the

drawdown is on the order of 25 percent of the initial aquifer thickness (*i.e.*, 95 feet divided by 400 feet).

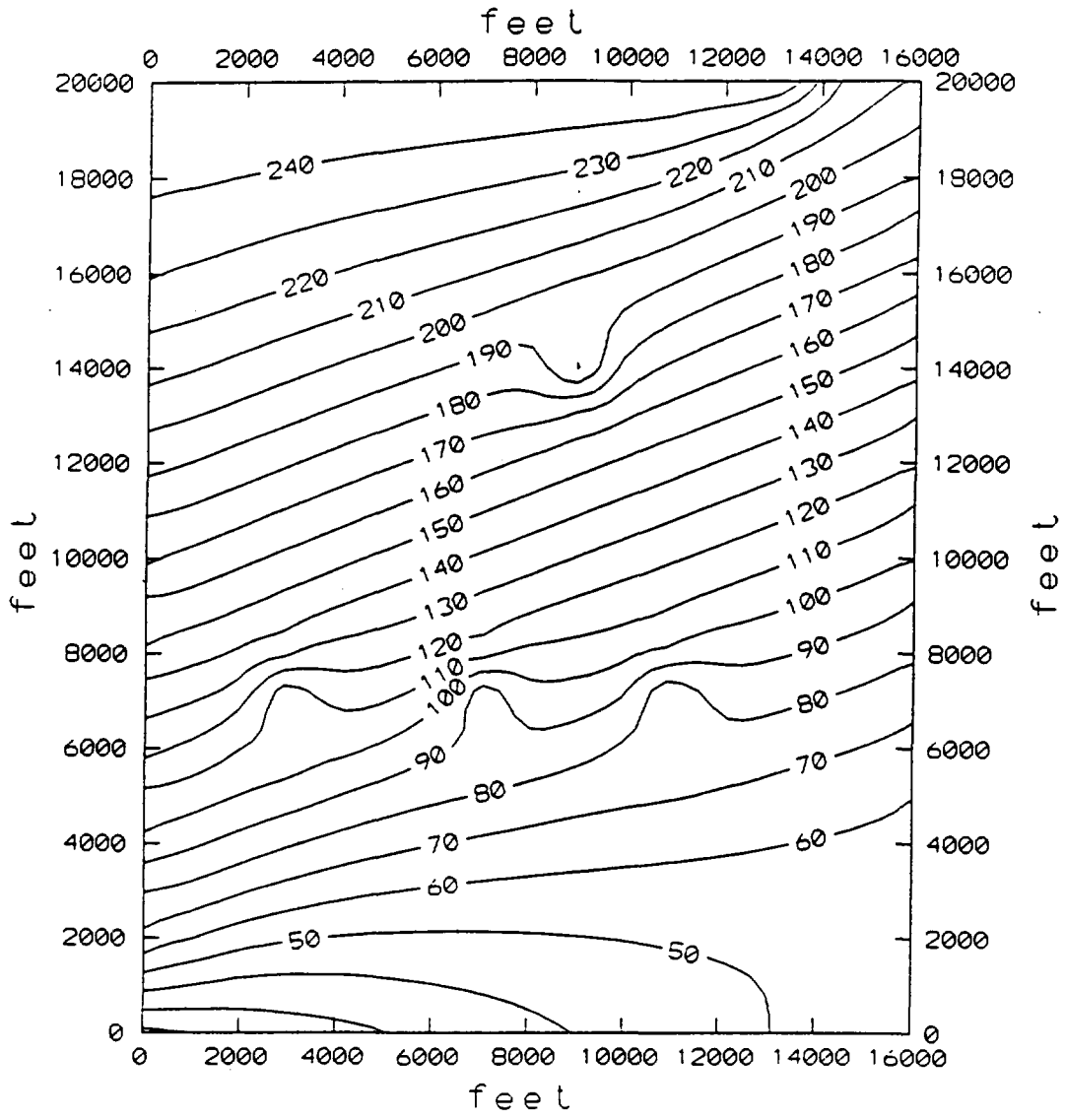
Finally, the steady-state head distribution for the same problem was computed using SUTRA. The result (Figure 8c) is identical to confined aquifer solution obtained with ARMOS (Figure 8b), indicating that ARMOS and SUTRA give identical results when the aquifer thickness is consistent. This confirms that the differences between transient simulation results at later times for the two models are due to the assumption of confined aquifer flow in SUTRA. The results verify the accuracy of the ARMOS water flow solution for conditions involving pumping and recharge in an anisotropic aquifer, and also stress the need for caution in applying confined aquifer solutions for unconfined cases, and visa versa.

Figure 5a



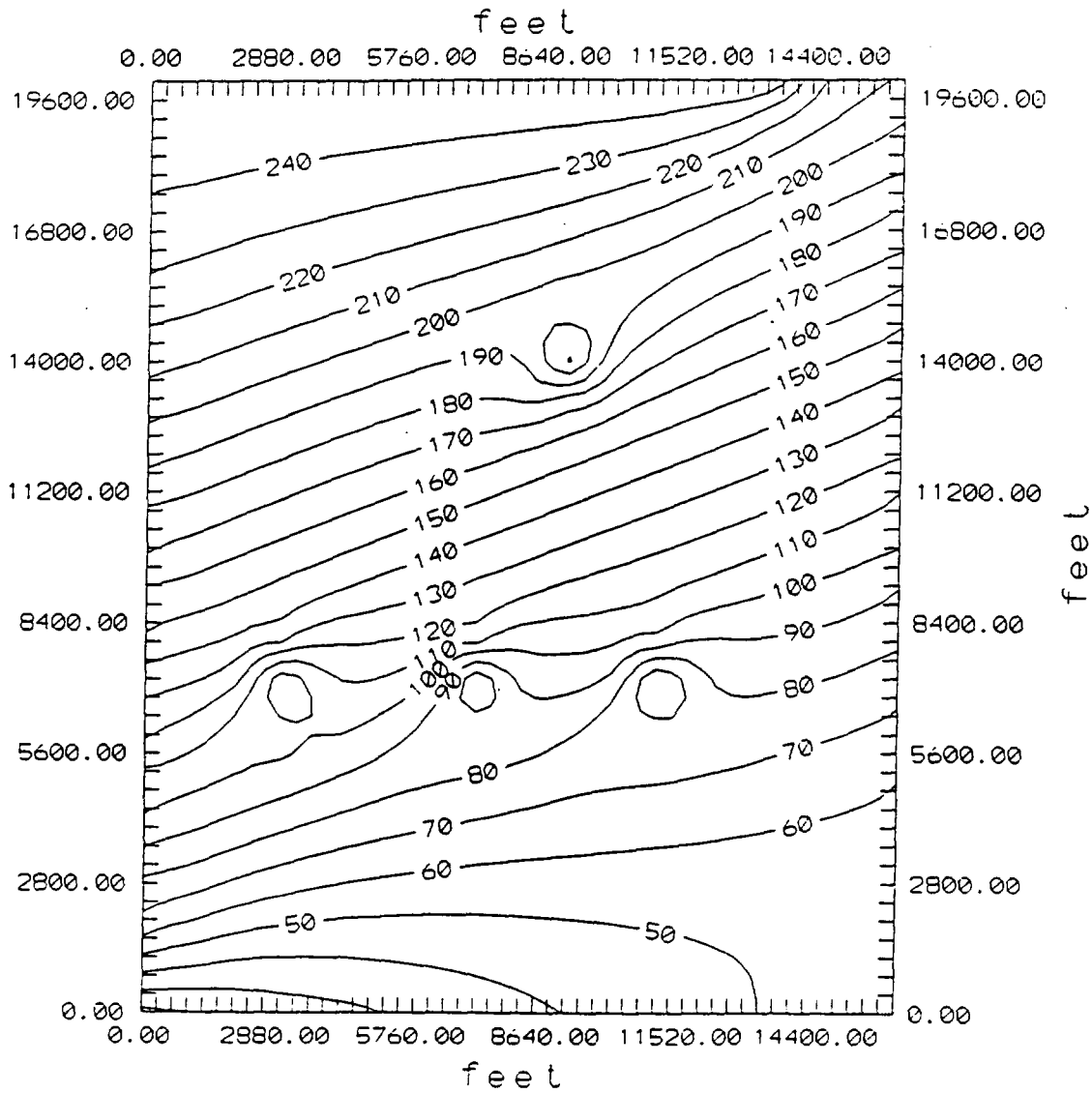
Hydraulic head for transient flow at 5 days using ARMOS.

Figure 5b



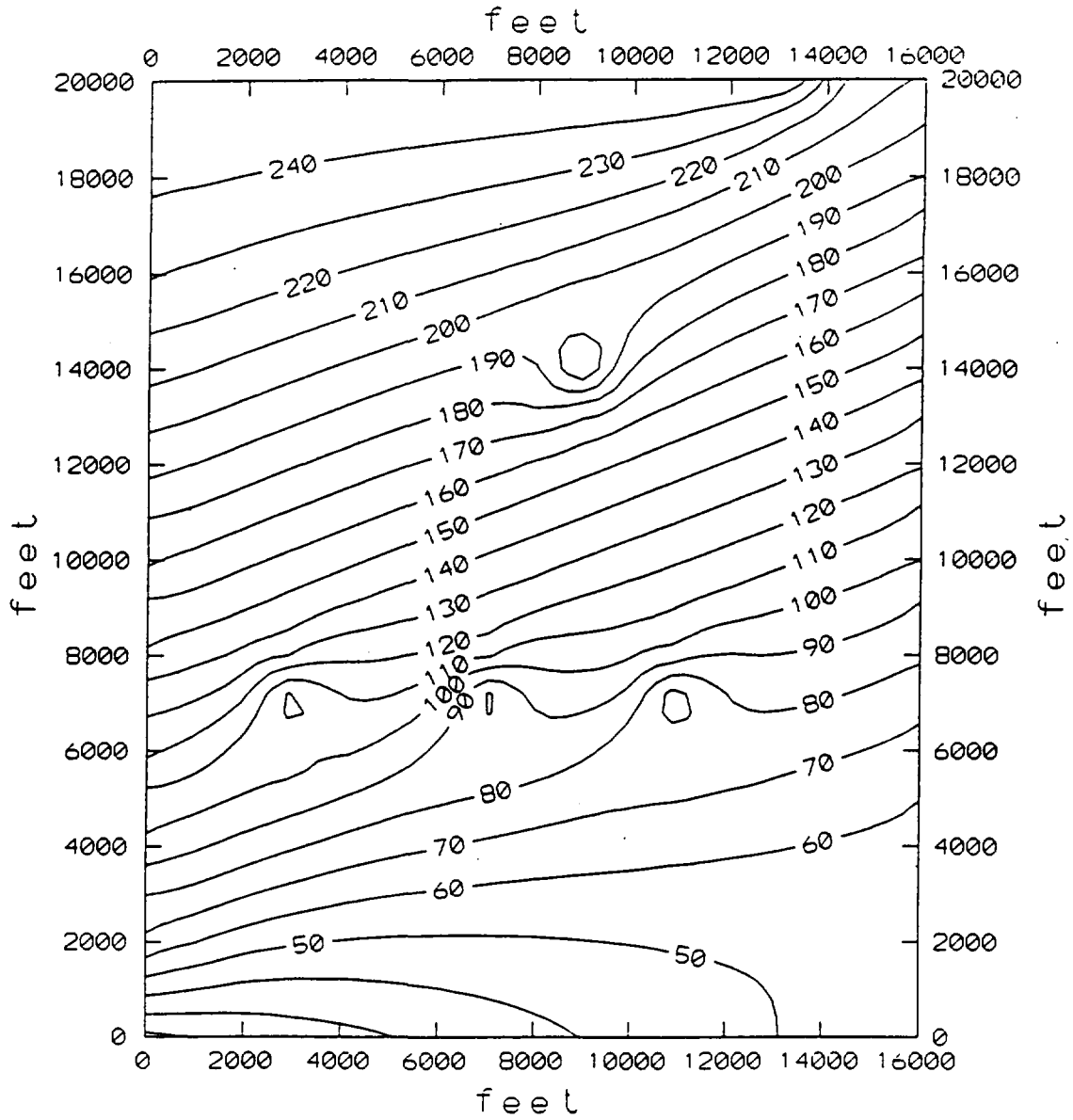
Hydraulic head for transient flow at 5 days using SUTRA.

Figure 6a



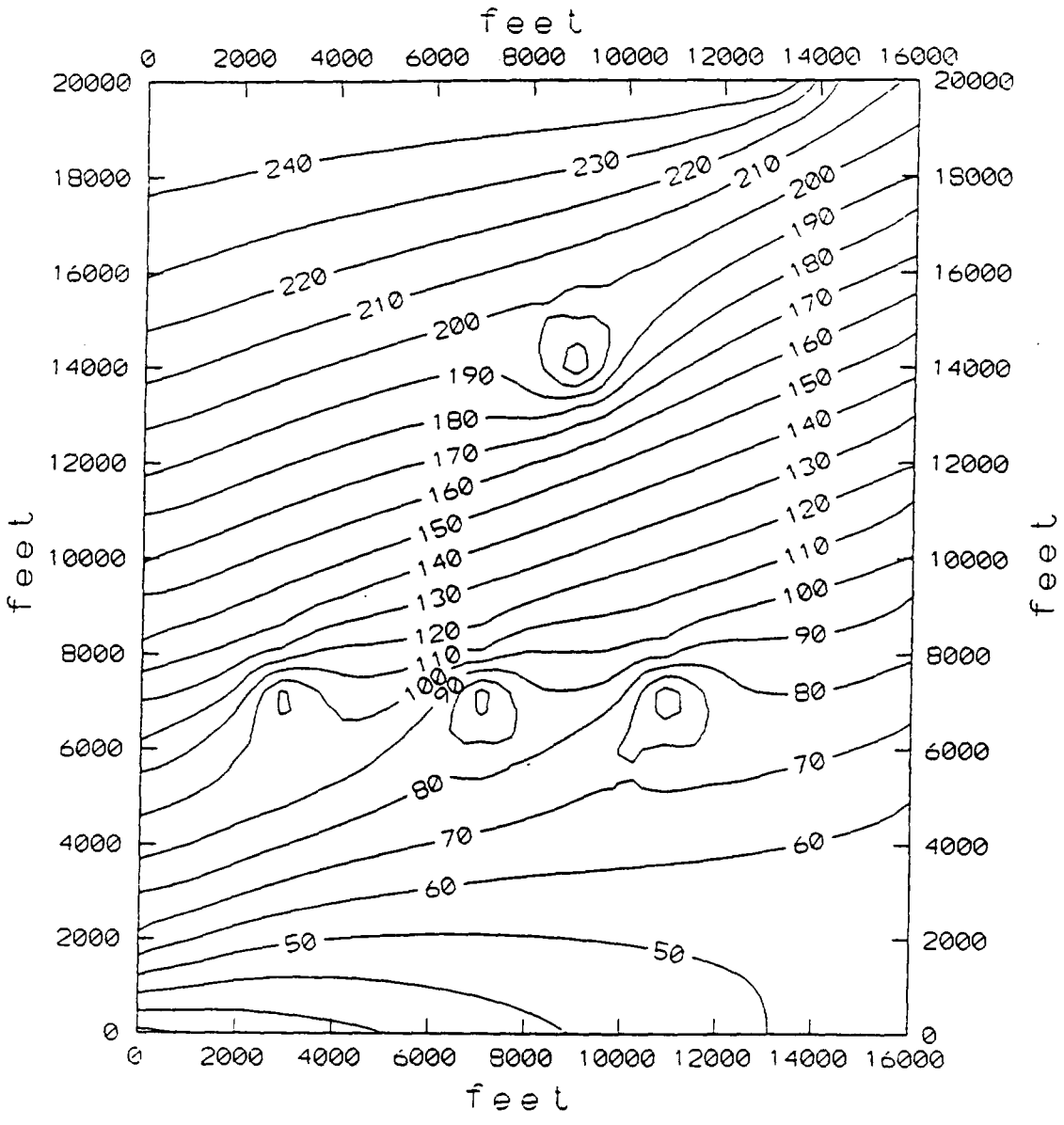
Hydraulic head for transient flow at 10 days using ARMOS.

Figure 6b



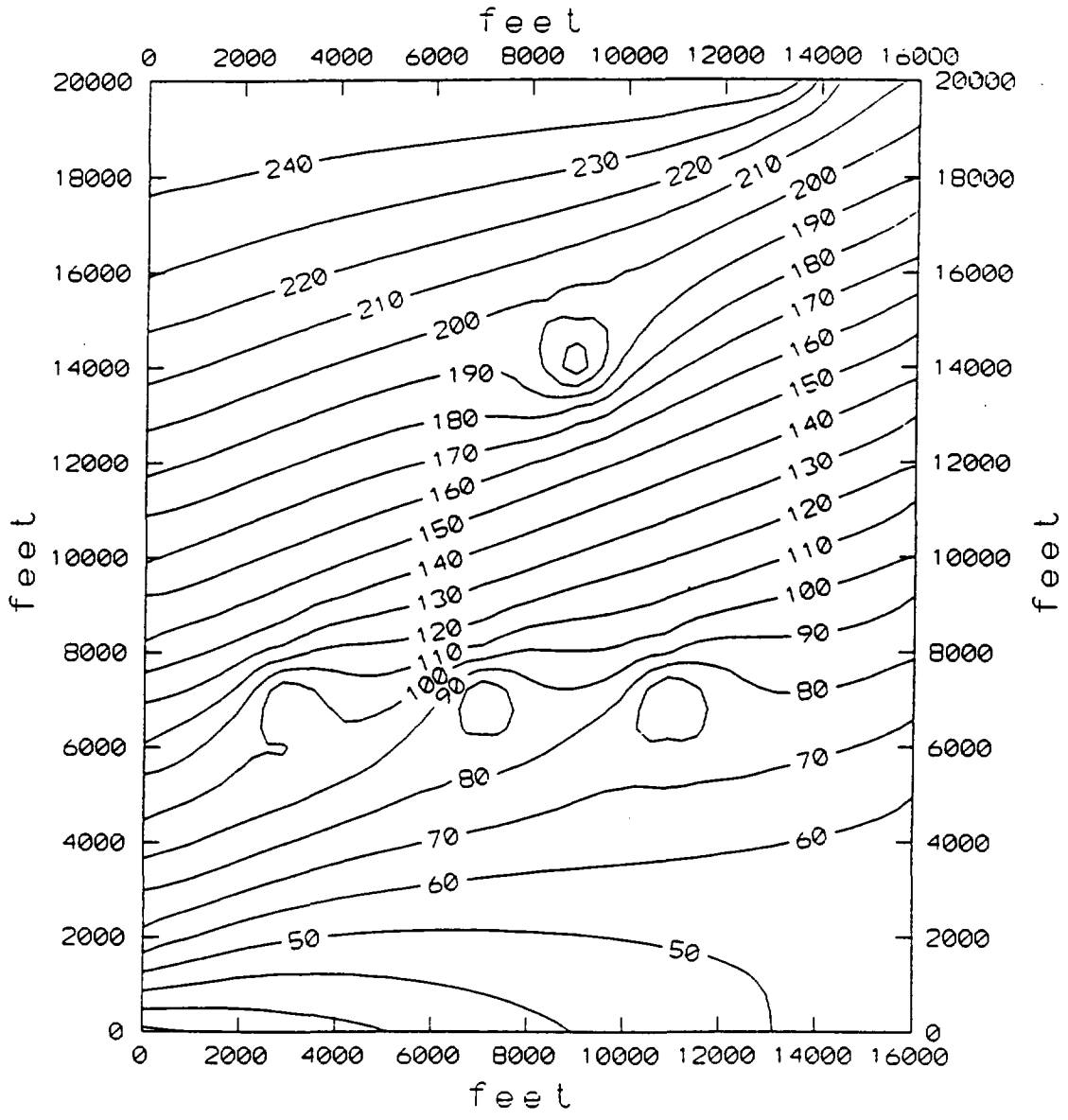
Hydraulic head for transient flow at 10 days using SUTRA.

Figure 7a



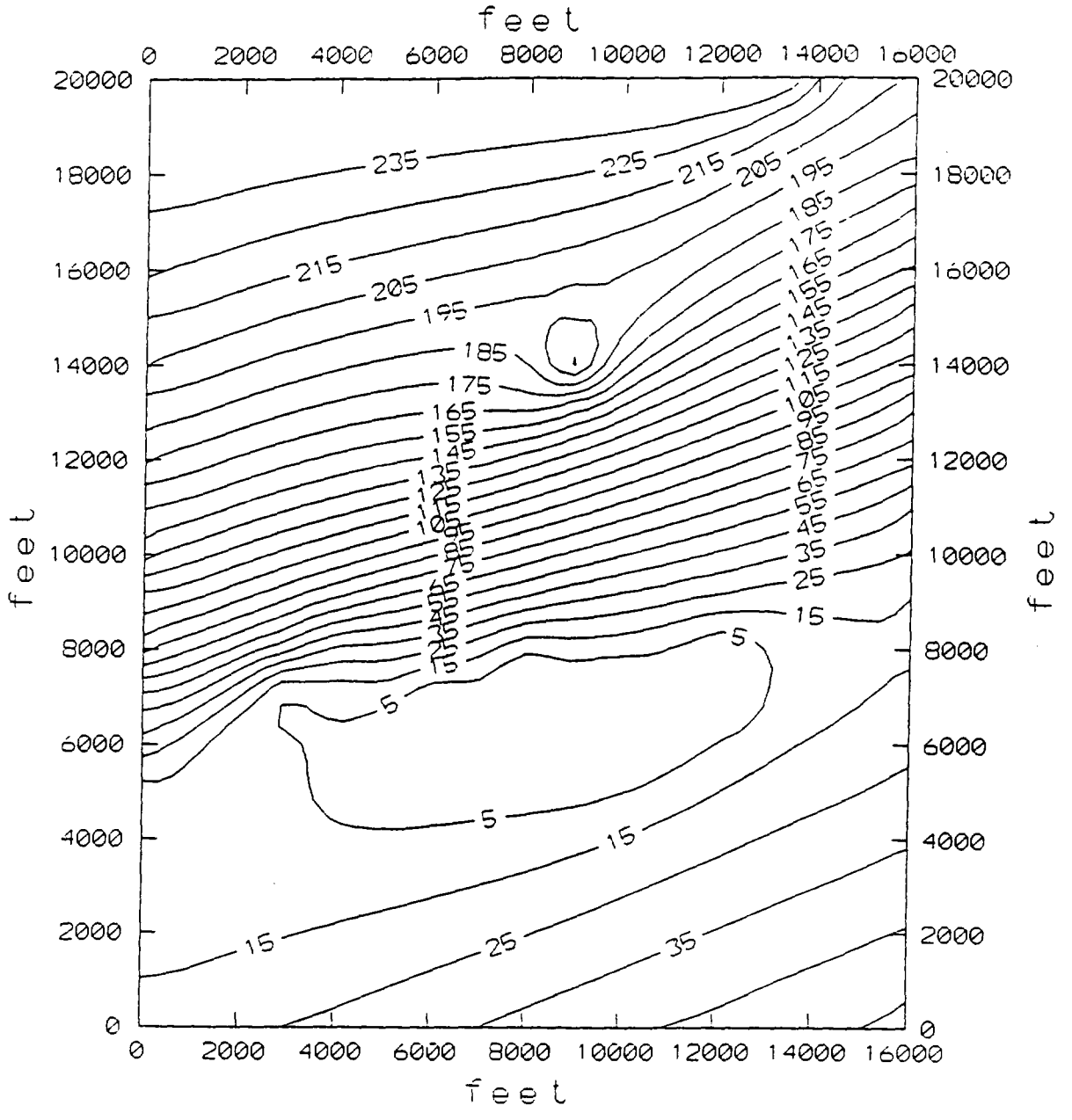
Hydraulic head for transient flow at 20 days using ARMOS.

Figure 7b



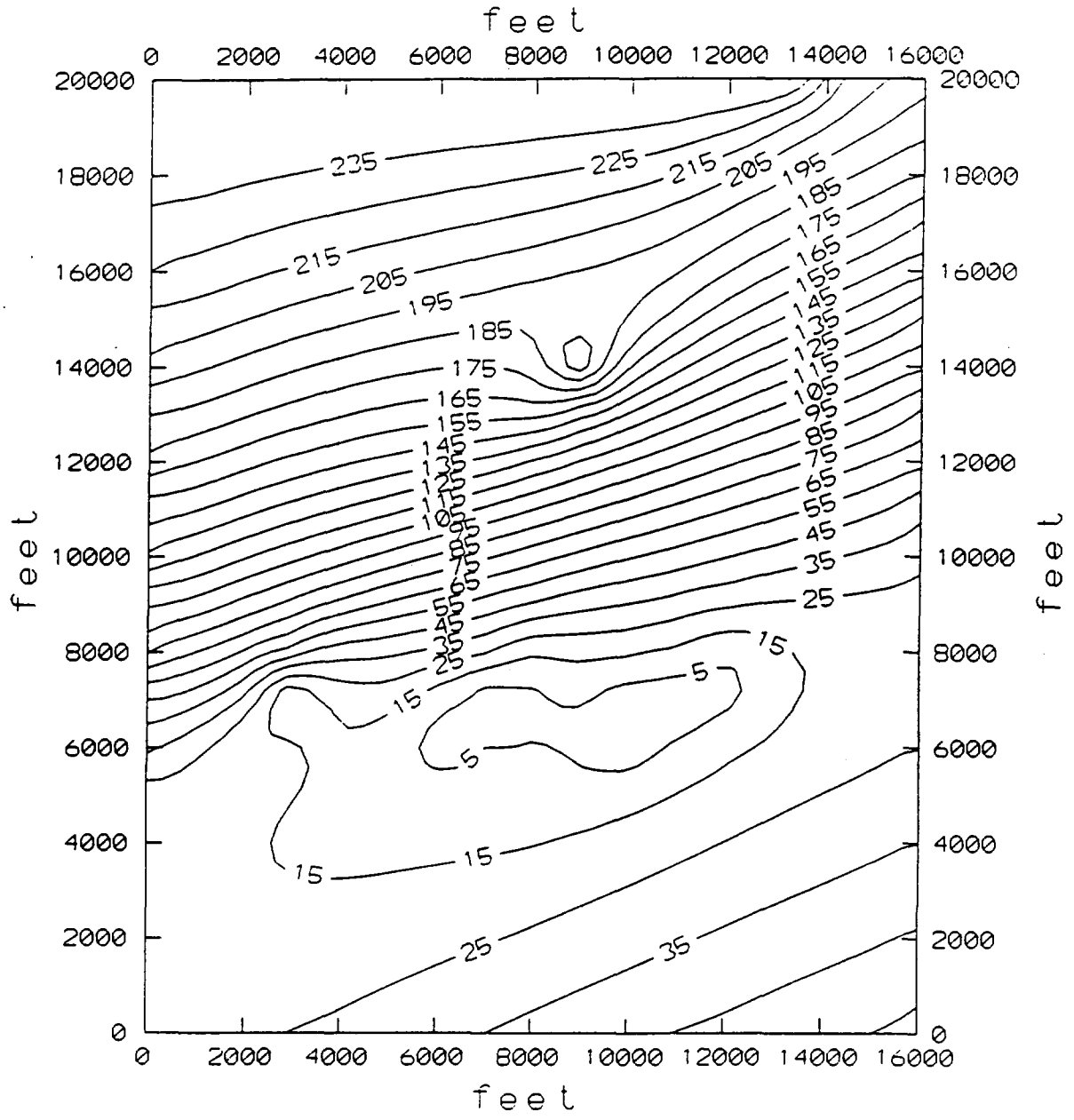
Hydraulic head for transient flow at 20 days using SUTRA.

Figure 8a



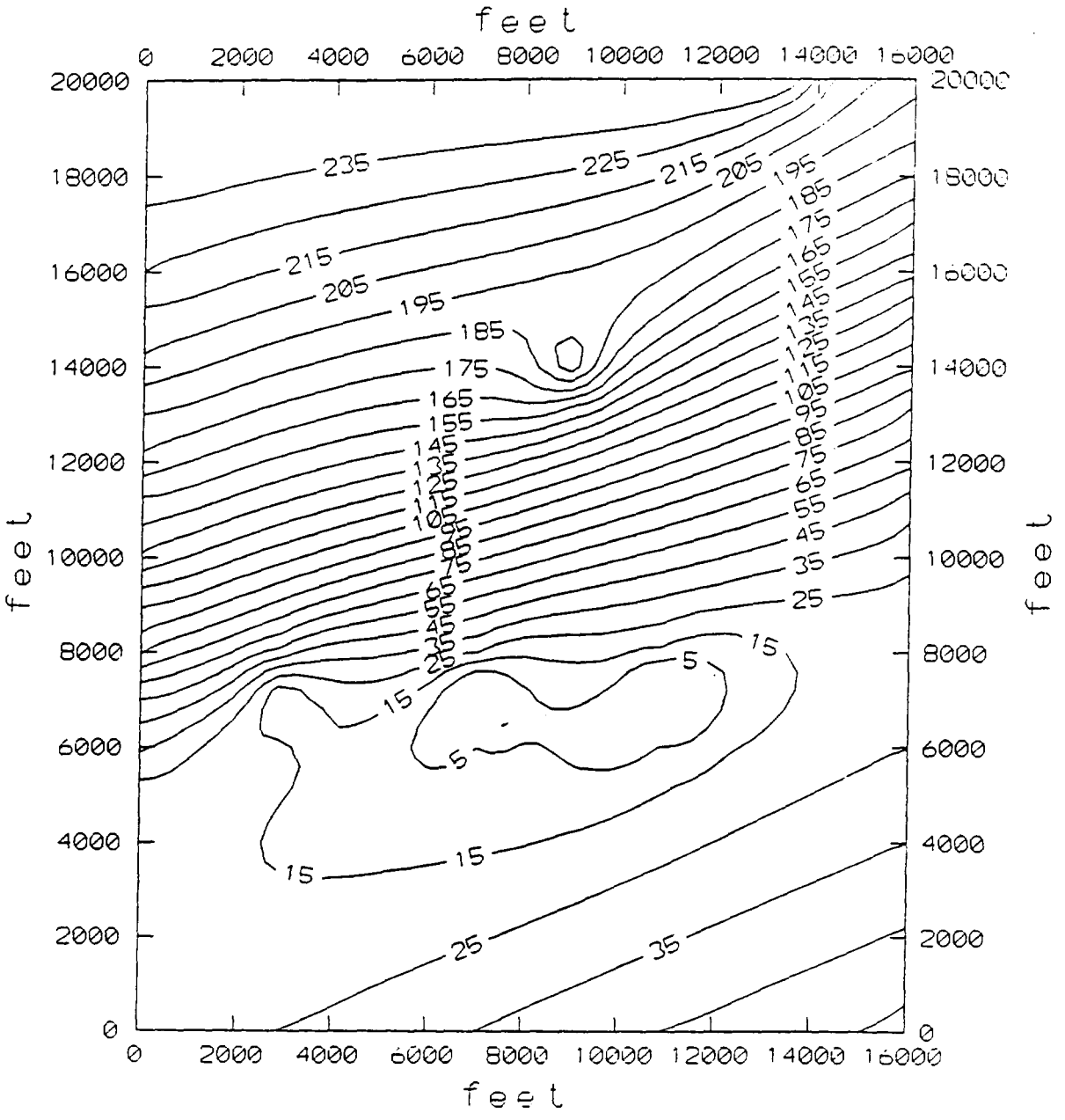
Steady-state flow with pumping for unconfined flow using ARMOS.

Figure 8b



Steady-state flow with pumping for confined aquifer using ARMOS.

Figure 8c



Steady-state flow with pumping for confined flow using SUTRA.

6.3 Oil Flow Model Verification

6.3.1 Comparison with analytical solutions

The oil flow solution in ARMOS was tested by comparison with analytical solutions for cases involving steady-state oil flow with a constant gradient and for transient oil recovery with a constant oil pumping rate under simplified conditions that permit an analytical solution to be obtained. The domain for the numerical problem is 500 X 500 feet with a well at the center. The grid spacing for ARMOS is 6 feet at the well and increases to 10 feet at the outer perimeter. The aquifer is characterized by an isotropic hydraulic conductivity (K_{sw}) of 10 feet/day, a porosity (ϕ) of 0.35, a field capacity water saturation (S_m) of 0.1, and capillary parameters of α=5 feet^{-1} and n=1.5. Fluid properties corresponding to a light fuel oil are ρ_{ro}=0.8, η_{ro}=1.2, β_{ao}=3.0 and β_{ow}=1.5.

Steady-state oil flow. The first problem involves an aquifer with a lower elevation at Z=0, an initial uniform air-oil table (Z_{ao}) at 50 feet, and a uniform oil thickness (H_o) of 2, 5 or 10 feet. Air-oil and air-water table elevations at the pumping well were set 2, 5 or 10 feet below the initial levels, such that the oil thickness at the well was maintained constant, with water pumping and oil pumping at the well. Boundary conditions for ARMOS involve fixed fluid table elevations on the outer perimeter at the initial conditions and fixed heads on the well node corresponding to specified water drawdown and oil thickness. Steady-state water and oil pumping rates at the well were determined using ARMOS and compared with results computed from steady-state analytical solutions. For the oil phase, since oil transmissivity is constant, the solution has the same form as the solution for steady confined aquifer flow (*e.g., Freeze and Cherry*, 1978) as

$$Q_o = 2\pi T_o \frac{\Delta Z_{ao}}{ln\,(R_o/R_w)} \qquad (6.1)$$

where Q_o is the oil pumping rate, T_o is the oil transmissivity corresponding to the specified oil thickness, ΔZ_{ao} is the difference in the air-oil table on the domain perimeter, R_w is the well radius (taken to be 0.25 ft), and R_o is the effective domain radius computed as $(A/\pi)^{1/2}$ where A is the area of the rectangular model domain. For the assumed soil and fluid properties, oil transmissivity was computed

to be 4.9, 19.0 and 46.5 feet^2/day for H_o = 2, 5 and 10 ft, respectively, following the equations presented in Chapter 2. For the water phase, the solution for steady unconfined flow (*Freeze and Cherry*, 1978) is

$$Q_w = \pi K_{sw} \frac{Z_o^2 - Z_w^2}{ln\,(R_o/R_w)} \qquad (6.2)$$

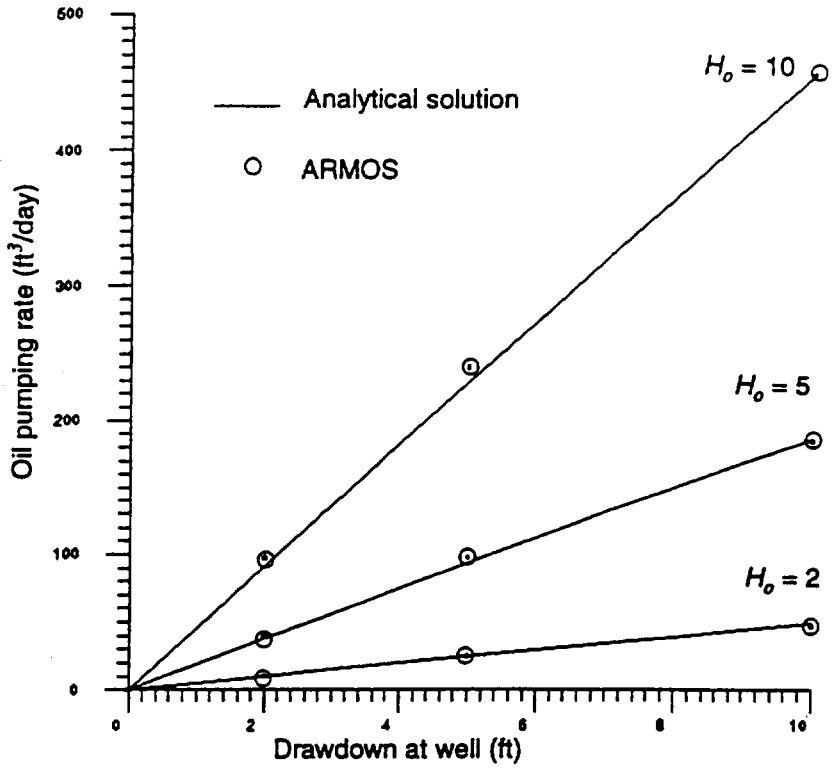
where Q_w is the water pumping rate, K_{sw} is the saturated hydraulic conductivity, Z_o the oil-water table elevation in the outer boundary, Z_w is the oil-water table elevation at the well, and R_o and R_w are as defined previously. Equation (6.2) assumes water transmissivity is controlled by the oil-water table elevation and that the oil-water table is parallel to the air-water table (which is the driving force for water flow).

A comparison of the analytically computed oil pumping rates versus well drawdown for apparent oil thicknesses of 2, 5 and 10 feet is shown in Figure 9. Water pumping rates versus well drawdown from the numerical and analytical models are compared in Figure 10. Numerical model results compare closely with the analytical results. Increasing the well drawdown (*e.g.*, reducing pump intake level for water and oil) increases the pumping rates for water and oil linearly, or nearly so. Increasing oil thickness produces a large increase in oil pumping rate, reflecting the increased oil transmissivity, and a small decrease in water pumping rate, reflecting the small decrease in water transmissivity with increasing oil thickness.

Transient oil flow. The second analytical verification problem for the oil flow solution considers transient oil pumping at a constant rate from a well. The same domain and soil and fluid properties used in the preceding steady-state case were assumed, with the initial air-oil table at 100 feet and the initial oil-water table at 90 feet. The initial fluid levels are maintained on the outer perimeter of the domain throughout the simulation for the numerical solution. Oil pumping is imposed at a constant rate of 10 ft^3/day in the well, and no water is pumped. Because the initial and boundary conditions do not result in a large change in oil thickness relative the initial thickness, oil transmissivity changes little from the initial value of 46.5 feet^2/day. Thus, the Theis solution may be applied to the oil flow problem to compute the air-oil table drawdown versus time. A comparison of the analytically and numerically computed air-oil table elevation versus time for observations wells 7.9 and 18.4 feet from the pumping well is given in Figure 11. Good agreement is observed. The small differences observed at larger times probably

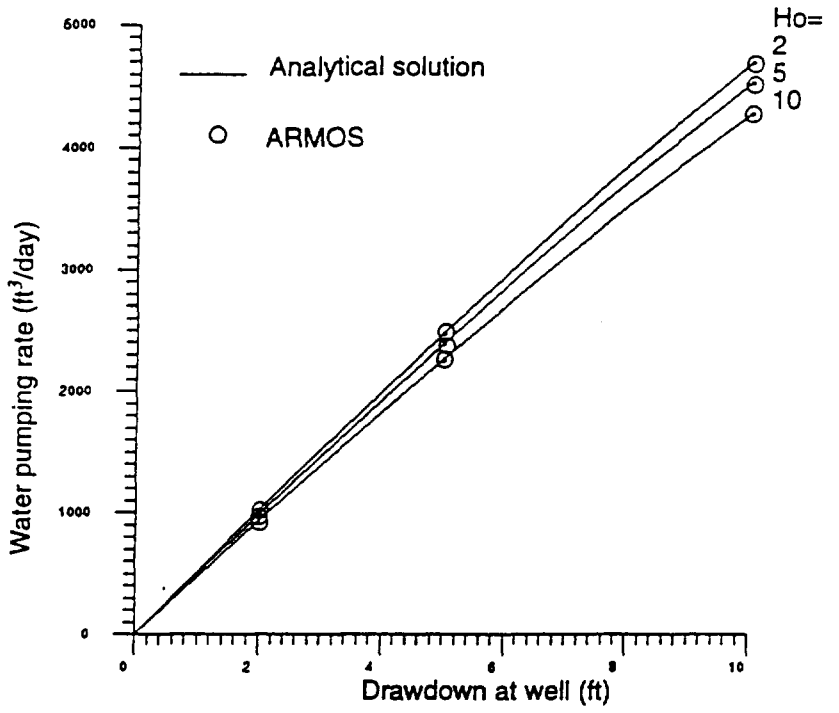
reflect deviations from the assumption of constant oil transmissivity in the analytical model.

Figure 9



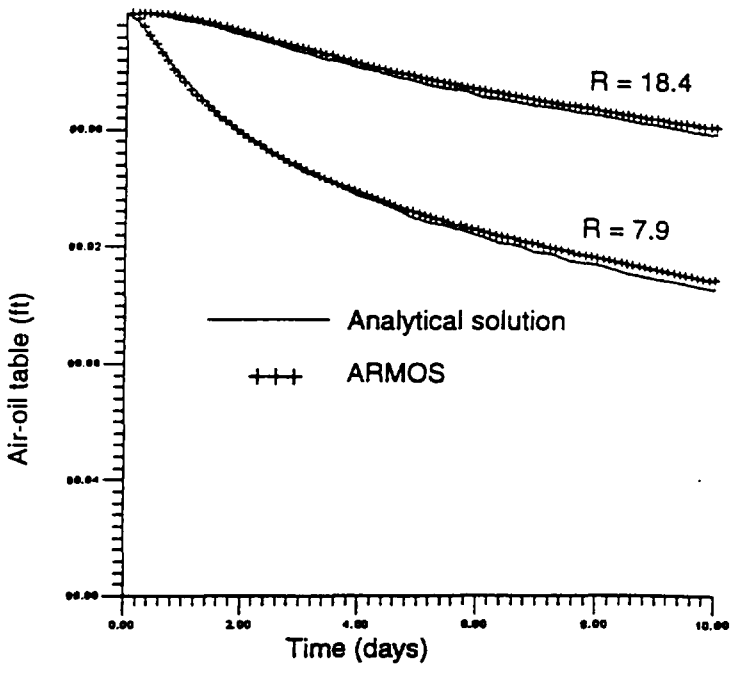
Steady-state oil pumping rate versus well drawdown for different well oil thicknesses (H_o = 2, 5, 10 ft shown on curves) during two-phase flow.

Figure 10



Steady-state water pumping rate versus well drawdown during two-phase flow for different well oil thicknesses (H_o = 2, 5, 10 ft shown on curves)

Figure 11



Air-oil table versus time with constant oil pumping for ARMOS and analytical model.

6.3.2 Comparisons With MOTRANS

ARMOS results were also compared with the model MOTRANS (*ES&T*, 1990), which is a finite element model capable of simulating fully coupled flow of water, oil and air in vertical cross-sections. The problem involves oil and water flow to a trench under conditions with a constant oil thickness and gradient. The problem is similar to the case analyzed analytically, but provides an independent check of the oil specific volume and transmissivity calculations in ARMOS for vertical equilibrium conditions. The physical domain of the problem is taken to be a region 3 meters long in the direction of flow, 1.5 meters tall and unit width along the trench. MOTRANS considers a vertical cross-section of the domain discretized by a 16 X 16 node mesh, and ARMOS considers a plan view of unit width with a 16 X 2 node mesh. Soil properties are assumed to be homogeneous and isotropic with a hydraulic conductivity (K_{sw}) of 10 meters/day, a porosity (ϕ) of 0.4, a residual water saturation (S_m) of 0.1, and capillary properties of α=2.0 m^{-1} and n=1.5. Fluid properties are taken as ρ_{ro}=0.8, η_{ro}=2.3, β_{ao}=3.0 and β_{ow}=1.5, similar to diesel fuel.

The problem considers steady-state flow of water and oil with water and oil pressures specified on the upgradient and downgradient boundaries and no-flow conditions on all other boundaries. Simulations with ARMOS imposed Z_{aw}=0.68 meters and Z_{ao}=0.85 meters on the inflow boundary, corresponding to an oil thickness of 0.85 meters, and specified Z_{aw} and Z_{ao} levels on the downstream face, such that gradients for both phases of 1 or 5 percent were maintained. For MOTRANS, water and oil pressures on inflow and outflow boundaries were imposed, corresponding to the table elevations used in ARMOS runs and assuming vertical equilibrium. Vertically integrated oil contents and boundary fluxes were computed from MOTRANS by numerically integrating nodal values. The oil volume computed by ARMOS was 15.7 liters per square meter and MOTRANS gave 15.4 liters per square meter, corroborating the vertical oil integration. Vertically integrated steady-state oil fluxes at the trench boundary are summarized in Table 1 for the two models. The results agree within 3-5 percent. The deviations that occur likely reflect errors in MOTRANS due to limited vertical mesh resolution. Vertical integration in ARMOS can be performed with greater accuracy, because it is done outside the numerical solution with very fine vertical resolution. It is interesting that the ratio of oil fluxes for the 1 percent and 5 percent gradient cases is somewhat less than 5 for both ARMOS and MOTRANS, which may be attributed to a nonuniform gradient across the domain caused by a gradual decrease in water transmissivity near the trench.

Table 1. Steady-state oil flux from ARMOS and MOTRANS.

Oil Gradient	Oil Flux (liters/day)	
	ARMOS	MOTRANS
1%	1.65	1.58
5%	7.91	7.71

6.4 Optimizing Recovery for a Gasoline Spill

As an example application, we will consider a hypothetical problem involving a gasoline spill in an unconfined sandy aquifer. The assumed soil and fluid properties are given in Table 2. The domain of the problem is a 656 feet (north-south) X 820 feet (east-west)

region. The southwest corner of the domain is designated by the areal coordinates (0,0). The domain is initially free of oil and the water table slopes from an elevation of 32.8 feet on the west boundary to 25.9 feet on the east boundary (water gradient = 32.8-25.9/820 = 0.8%). Throughout the simulation, the air-water table (*i.e.*, Z_{aw}) is maintained at the initial levels on the domain perimeter. The lower elevation of the aquifer is assumed to be at a constant elevation of sea level ($Z = 0$). The finite element mesh consists of 357 nodes with a uniform spacing of 41 feet in both directions. Pumping simulations utilized 24 additional mesh refinement nodes near the well.

Table 2. Soil and fluid properties for example problem.

$\rho_{ro} = 0.75$	$K_{sw} = 32.8\, ft\, d^{-1}$	$S_m = 0.25$
$\eta_{ro} = 0.6$	$\phi = 0.35$	$S_{og} = 0.05$
$\beta_{ao} = 3.2$	$\alpha = 3.0\, ft^{-1}$	$S_{or} = 0.20$
$\beta_{ow} = 1.5$	$n = 2.0$	

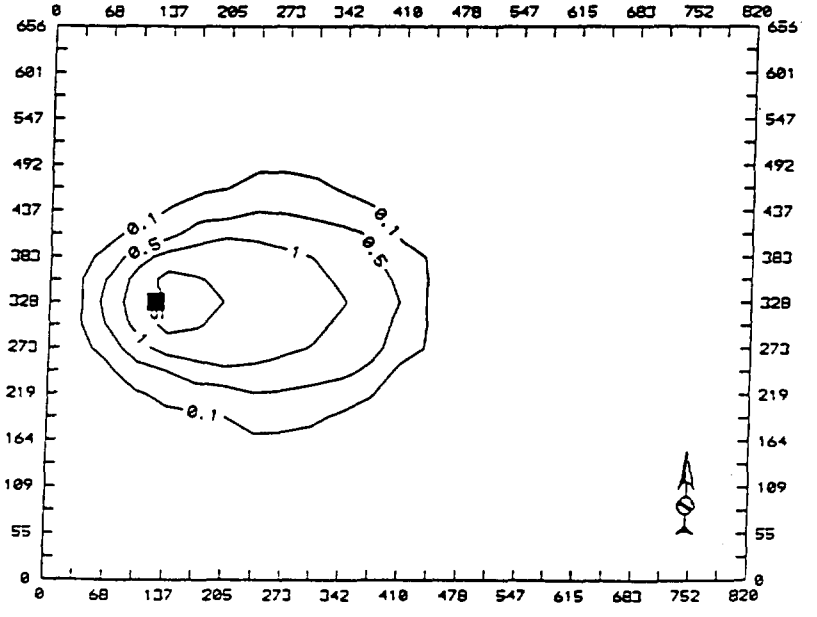
The first stage of the simulation involves a hydrocarbon leak of 132 gallons per day at north 328 feet and east 123 feet for a 200 day period, yielding a total spill volume of 26,400 gallons. The distribution of H_o at t=200 days is shown in Figure 12. The second stage of the simulation involves no water or hydrocarbon injection or pumping for a period of 100 days after the end of the leak event (to t=300 days). During this period, the hydrocarbon plume migrates with the natural hydraulic gradient. The distribution of well product thickness (H_o) at t=300 days is shown in Figure 13. Note that H_o only reflects the presence of free oil. Residual oil remains to the west along the migration path of the plume.

In the last stage of the simulation, water is pumped at a constant rate from a single recovery well located at north 328 feet and east 451 feet (Figure 13). Oil skimming is performed at a rate that maintains zero oil thickness in the recovery well. Simulations were conducted with water pumping rates ranging from 7 to 22 gallons per minute (gpm). The cumulative recovery versus time for each water pumping rate is shown in Figure 14. As water pumping rate is increased, the initial oil recovery rate (the slope of the cumulative recovery curve) increases. However, asymptotic recovery increases only up to a certain water pumping rate and then begins to decrease. This is illustrated more clearly in Figure 15, which shows final recovery versus water pumping rate. The optimum water pumping

rate for product recovery is about 15 gpm, which yields final free product recovery equal to 28% of the total spill volume.

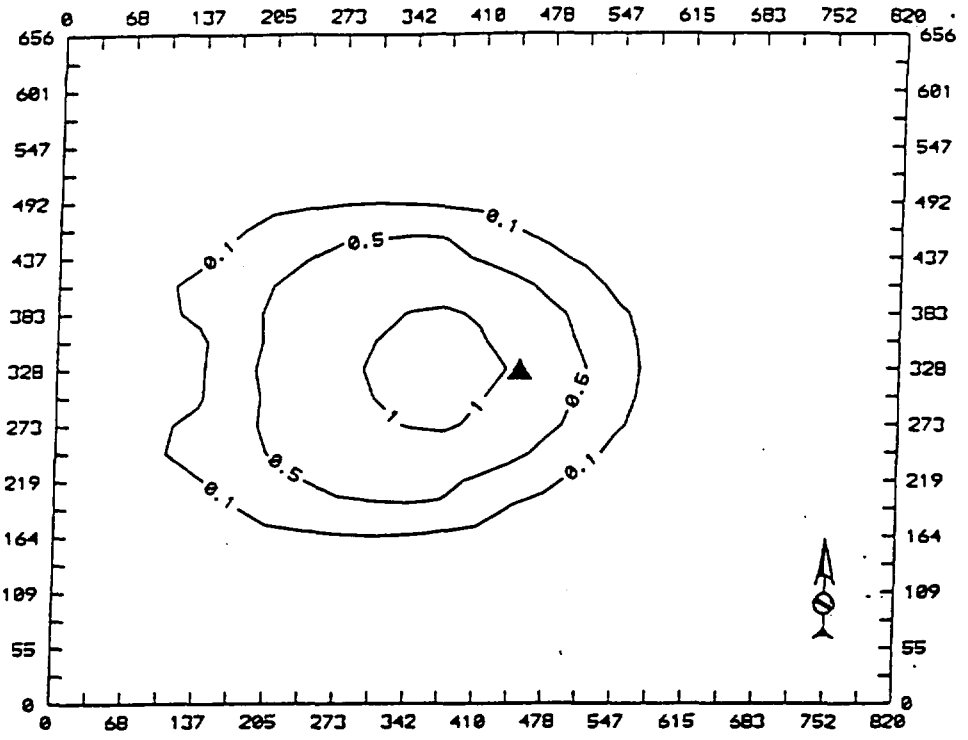
Why does product recovery exhibit a maximum at an intermediate water pumping rate? When the pumping rate is too low, hydraulic control of the free product plume is not achieved and lateral plume spreading leads to an increase in residual product. As pumping rate is increased, plume capture is achieved at a pumping rate of about 15 gpm. As the pumping rate is increased further, the cone of depression caused by pumping increases, leading to an increase in the unsaturated zone residual product, hence lower ultimate recovery. For a given initial hydrocarbon distribution and recovery system, the ultimate residual product and hence the asymptotic recovery will be controlled to a large extent by the magnitude of S_{or} and S_{og}. For the present problem, predicted recovery would exceed 90% of the spill volume if residual saturations were assumed to be zero, which is (unfortunately) far from what can actually be achieved!

Figure 12



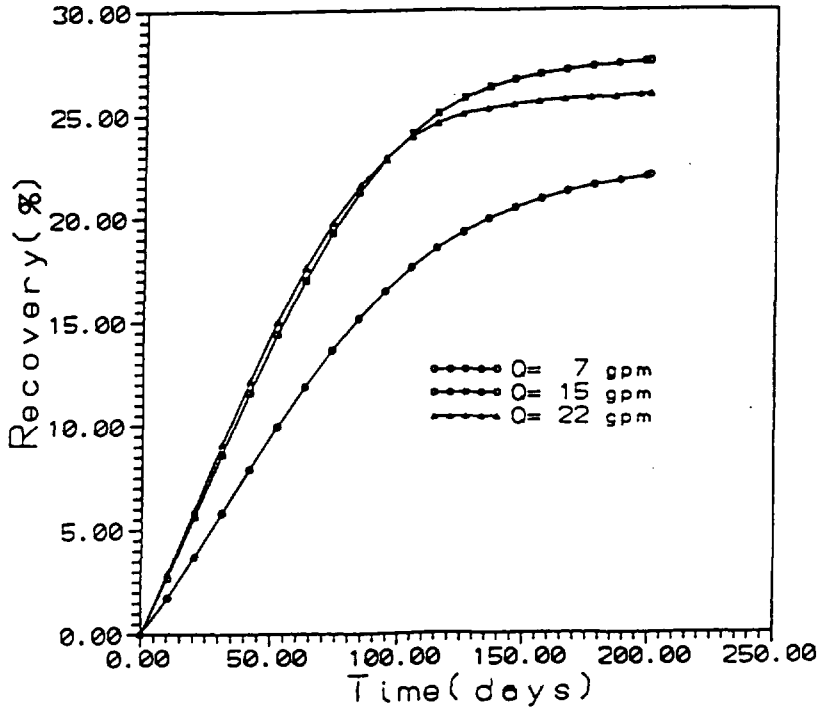
Well oil thickness after 200 day leak event for gasoline spill problem (leak site location shown as square).

Figure 13



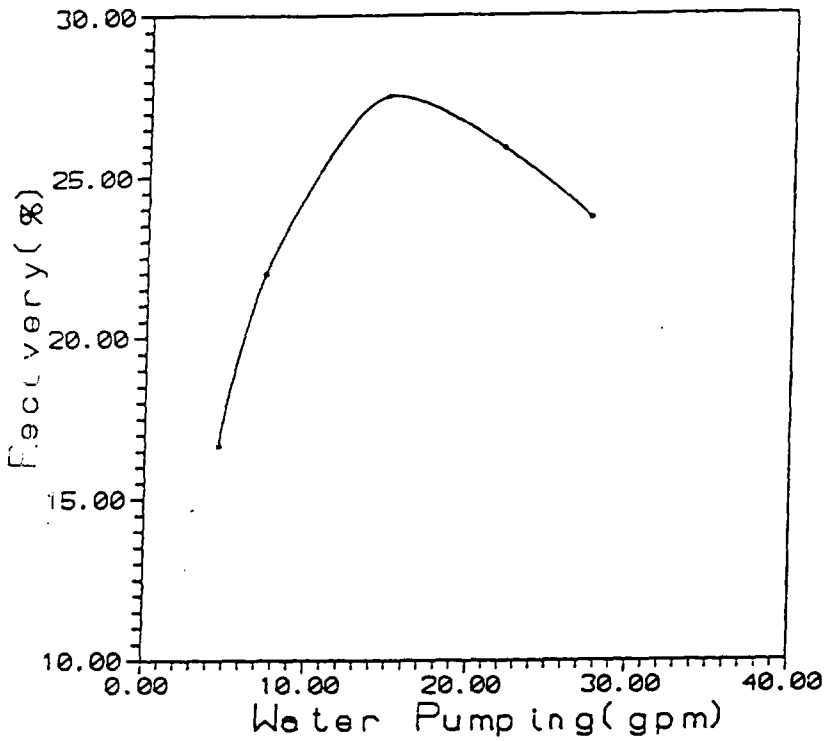
Well oil thickness at 300 days prior to initiating product recovery (recovery well location shown as a triangle).

Figure 14



Cumulative recovery versus time for different water pumping rates for gasoline spill problem.

Figure 15



Maximum recovery versus pumping rate for gasoline spill problem.

6.5 Field Application to Pipeline Leak

This problem involves an actual pipeline leak of gasoline, diesel and fuel oil. The soil at the site consists of coarse sand and gravel deposits and a water table occurs at a depth of 6 to 8 feet. Groundwater movement is in a westerly direction with a gradient of 1 to 5 feet per 1000 feet. Two recovery wells (RW-1 and RW-2) were initially employed to recover free product by skimming without water pumping. A third well (RW-3) began operating in a similar fashion three months later. Slightly under a year after beginning skimming, water pumping was initiated at all three wells to increase product recovery rates and to control nonaqueous and aqueous plume migration. Total water pumping rates for the three recovery wells averaged slightly over 200 gallons per minute over the entire period of operation. Product recovery rates averaged between 150 to 300 gallons per day before rather abruptly decreasing after 28 months.

The solution domain for ARMOS was taken to be a 1,350 X 1,300 feet area discretized by a mesh with 50 X 50 feet elements. Local mesh refinement was employed for the nearest four elements sur-

rounding each recovery well to reduce the mesh spacing near wells to 12 feet, bringing the total number of elements to 804 (Figure 16). The aquifer was assumed to have a uniform lower elevation of 32 feet (MSL), which is about 60 feet below the initial mean water table level (ca. 90 feet). Recovery wells were screened to a lower elevation of 70 feet, corresponding to a partial penetration of about 33% of the aquifer.

Initial conditions for the simulations (designated t = 0) were taken to correspond to the time when product skimming was initiated. Air-oil table and product thickness data from 45 monitoring wells at t = 0 were interpolated over the domain using a kriging algorithm.

Water table elevation fluctuations were determined by averaging changes in the corrected water table elevations versus time for several wells over the duration of the remediation period. The observed fluctuation data and a piecewise linear approximation used in the simulations are shown in Figure 17. The air-water table elevation at each boundary node was varied over time according to the fluctuation schedule (Figure 17), such that the regional water gradient remained constant throughout the simulation. Time varying recharge was applied at a rate equal to ϕ_e dZ/dt, where ϕ_e is the specific yield. A zero flux condition for the oil phase was imposed on the entire perimeter. Hydrocarbon skimming with no water pumping was simulated from RW-1 and RW-2 from $t = 0$ to 110 days and for RW-1, RW-2 and RW-3 from 110 to 341 days. Well boundary conditions during this period were zero water pumping rate and zero well bore oil thickness. Water pumping rates for the three recovery wells after $t = 341$ days were specified based on measured data for the individual wells. Values were averaged over time and imposed as constants for the numerical model, except for well RW-3, which exhibited a marked reduction in pumping rate for several months. Water pumping was initiated at 341 days, and was increased over a 33 day period up to 100 gpm for RW-1, to 60 gpm for RW-2 and to 51 gpm for RW-3. The pumping rates were maintained constant through the remainder of the simulation except for RW-3, which pumped at 22 gpm between t = 453 to 695 days. Oil boundary conditions during the water pumping period were specified the same as during skimming.

Hydrocarbon density, viscosity and scaling factors were taken as representative of a mixture of gasoline and diesel. Hydraulic conductivity was estimated from a pump test performed at the site. Average grain size distribution data from 6 soil samples (Table 3) were used to obtain initial estimates of the soil parameters (Table 4) using the program SOILPROP (*ES&T*, 1990; *Mishra et al.*, 1989),

assuming $\phi = 0.35$ and $S_m = 0.1$, which are typical for a sandy aquifer material. Initial estimates of the unsaturated and saturated zone residual saturations, S_{or} and S_{og}, were taken as 0.05 and 0.25, respectively, which are also representative for this type of material.

The initial free product volume based on the foregoing parameter estimates is 368,000 gallons. Predicted product recovery using the initial estimates of soil and fluid parameters is compared with measured recovery in Figure 18. The final recovery is underestimated by about 30%, although the predicted curve parallels the measured data rather closely. The time when product recovery rates drop substantially was slightly underestimated.

A second estimate of the parameters, α, n, S_{or} and S_{og}, which are subject to the greatest uncertainty, was obtained by fitting them to the product recovery data during the first 100 days of skimming. A least-squares nonlinear optimization algorithm (*Kool et al.*, 1988) was employed to carry out the parameter estimation operation. The revised parameter estimates are given in Table 5 and the corresponding predicted recovery curve projected over a three year period is shown in Figure 18. The final recovery is underestimated by about 20%. The spill volume estimated using the 100-day calibration parameters is 334,000 gallons.

A final calibration effort was made by fitting α, n, S_{or} and S_{og} to the full 950 days of product recovery data. The final parameter estimates (Table 5) yield a spill volume of 410,000 gallons. The predicted recovery versus time (Figure 18) indicates generally good agreement with the observed recovery data, as well as with product thickness data versus time data for monitoring wells (Figure 19). Particularly noteworthy is the inverse correlation between water table elevation (Figure 17) and well product thickness (Figure 19) which is predicted by the model due to trapping and untrapping of product associated with water table fluctuations.

The model did not predict the increased recovery rate at 150 days when skimming from RW-3 was initiated. Inspection of the spatial distribution of product suggests that this is due to underestimation of the initial product thickness near RW-3, since well gauging data was not available initially at this location.

Table 3. Grain size distribution data for pipeline leak site.

Size range (mm)	Percent in class (±std. dev.)
<0.1	2.5 ± 0.5
0.1-0.25	8.5 ± 3.0
0.25-0.5	48.0 ± 18.9
0.5-1.0	22.0 ± 4.8
1.0-2.0	7.2 ± 5.4
2.0-4.0	4.0 ± 1.5
>4.0	7.8 ± 8.0

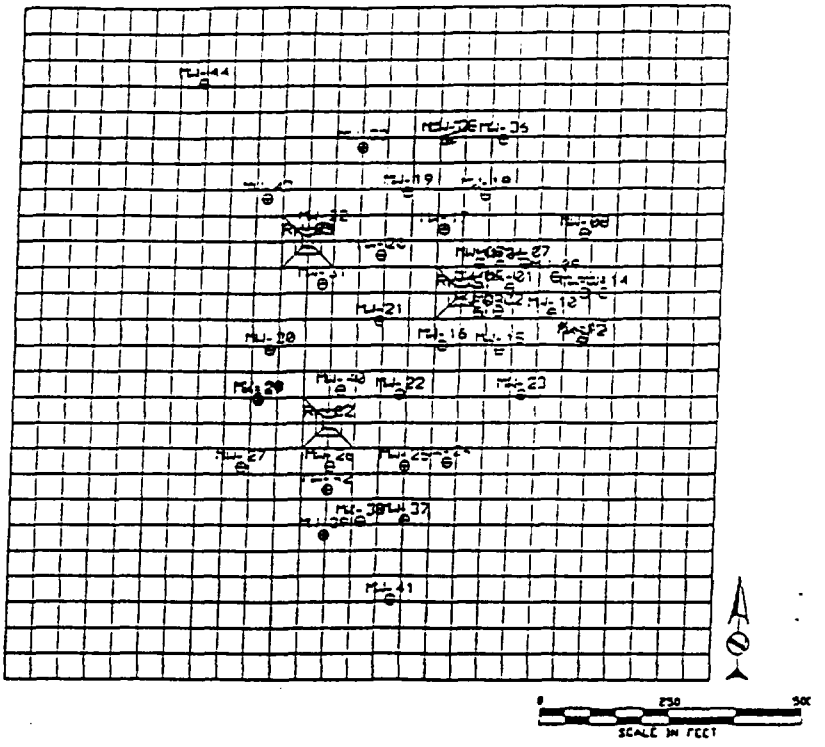
Table 4. Initial estimates of soil and fluid properties for pipeline leak site.

$\rho_{ro} = 0.80$	$K_{sw} = 290\, ft\, d^{-1}$	$S_{in} = 0.10$
$\eta_{ro} = 2.0$	$\phi = 0.35$	$S_{og} = 0.05$
$\beta_{ao} = 3.4$	$\alpha = 4.1\, ft^{-1}$	$S_{or} = 0.25$
$\beta_{ow} = 1.42$	$n = 2.0$	R=1

Table 5. Improved parameter estimates and corresponding estimated spill volume.

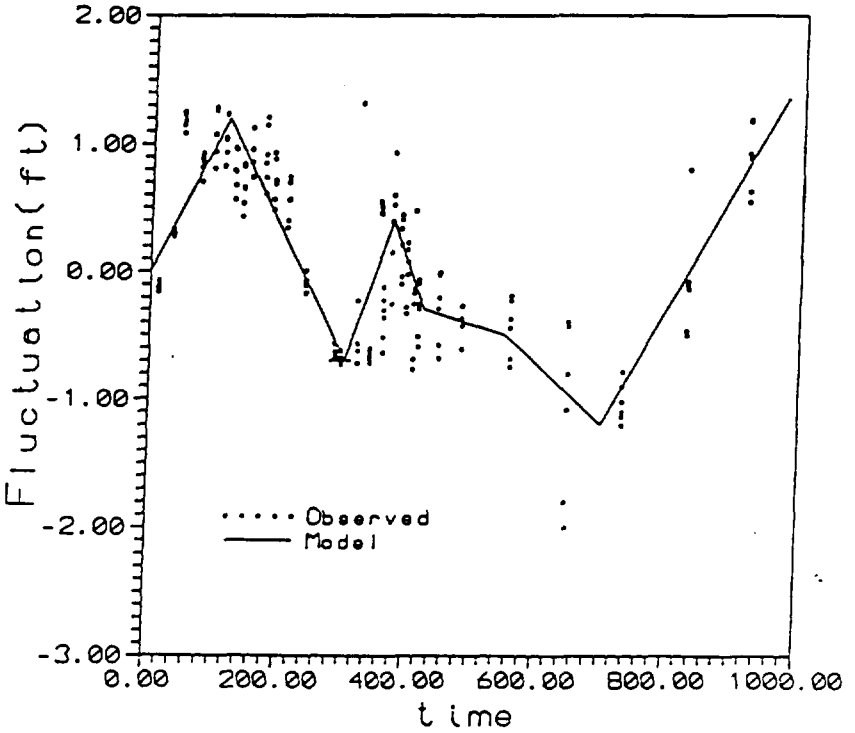
Method	α (ft^{-1})	n	S_{or}	S_{og}	Spill volume (gal)
Grain size data	4.1	2.0	0.25	0.050	368,000
100 day calibration	5.3	1.55	0.15	0.062	334,000
950 day calibration	4.2	2.25	0.145	0.051	410,000

Figure 16



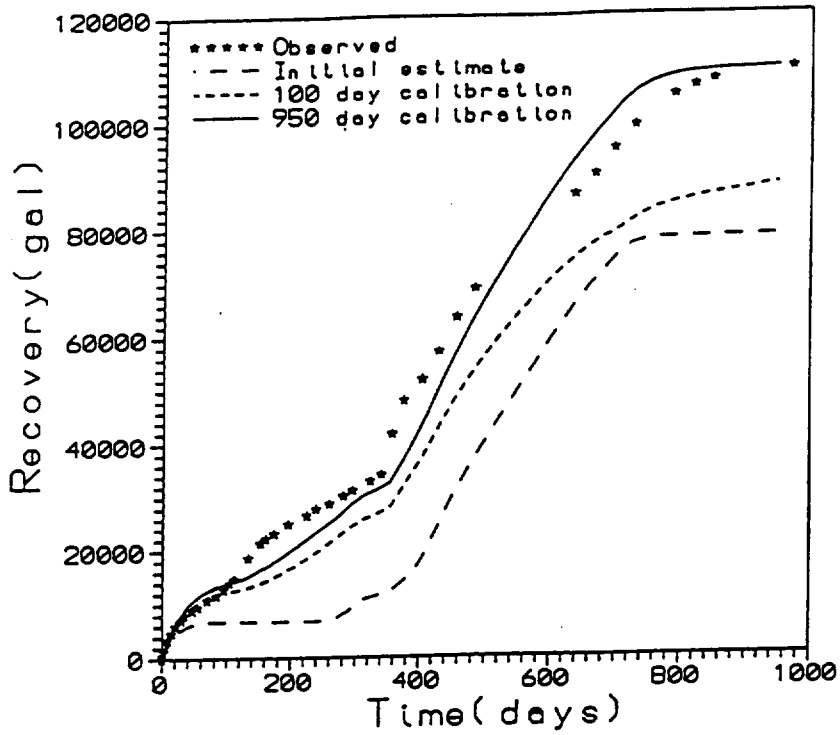
Monitoring well network and model domain for pipeline leak site.

Figure 17



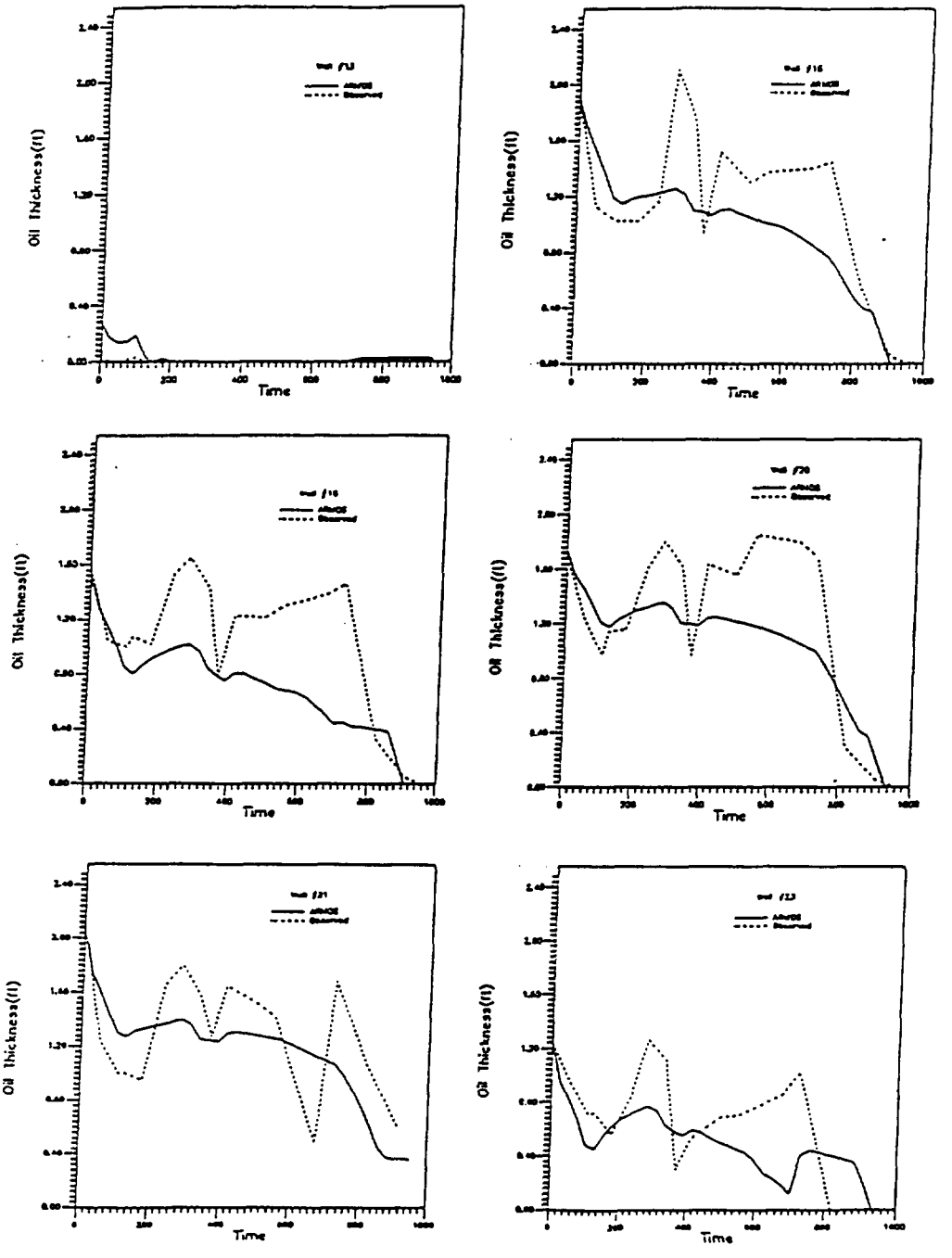
Observed water table elevation fluctuations and piecewise linear approximation for pipeline leak site.

Figure 18



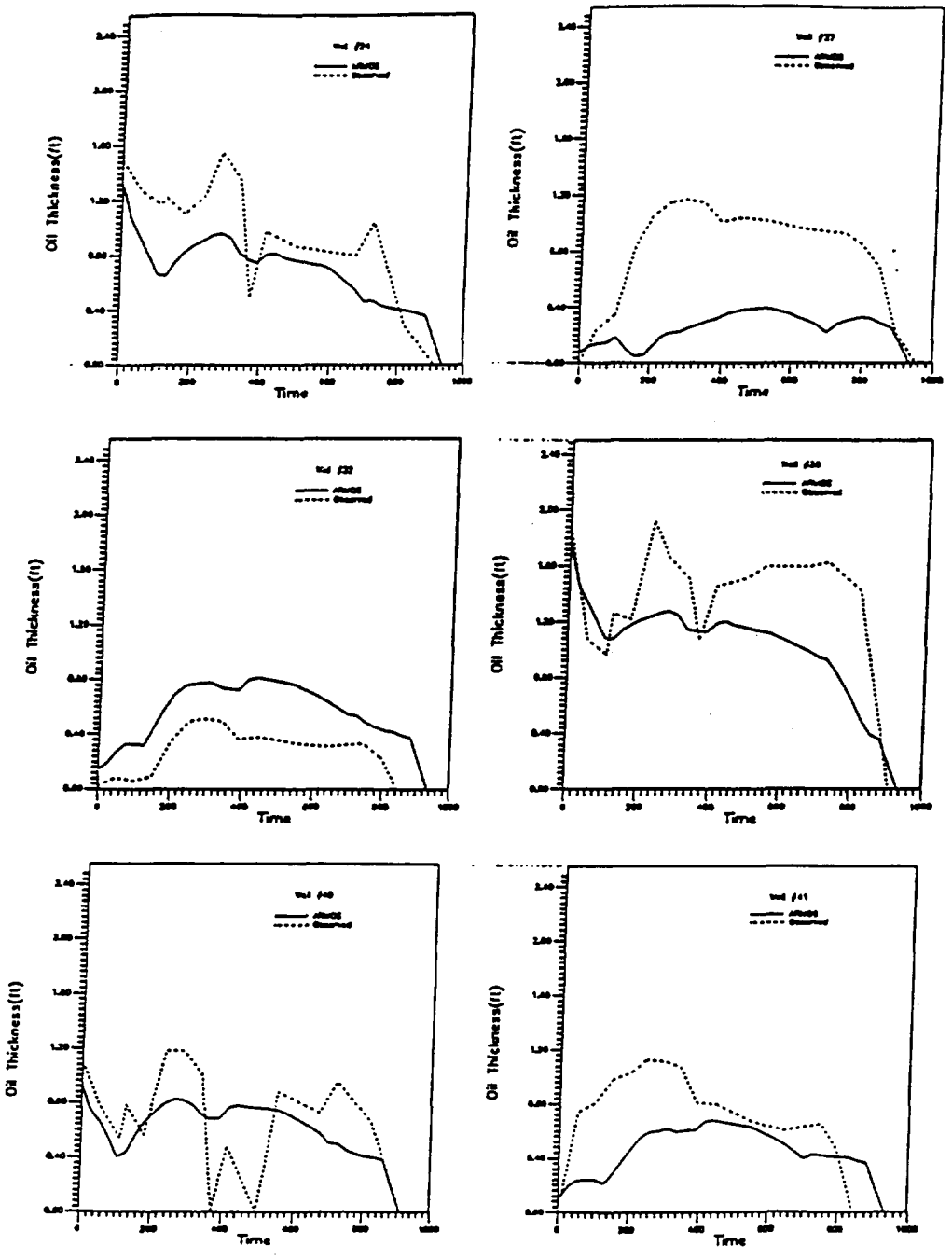
Observed and simulated cumulative product recovery for field site using various parameter estimates (see Table 4).

Figure 19a



Observed and predicted product thickness in monitoring wells for pipeline leak site.

Figure 19b



Observed and predicted product thickness in monitoring wells for pipeline leak site.

7. ARMOS Tutorial Problem

An example problem has been included with ARMOS to give you a hands-on demonstration of the program's capabilities. The data is pre-entered in the project file "TUTOR" on the ARMOS disk, so you can get some practice using the program without too much difficulty. You will want to read through the first three chapters of this manual to get ARMOS loaded, and to get familiar with basic operations of the graphical user interface. You may want to refer to the first three chapters while reading through this tutorial to get additional information on a current subject.

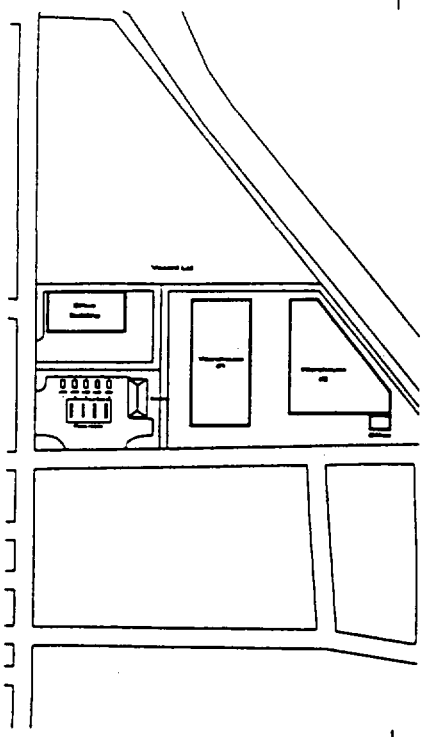
To load the project, open it as you would any other existing project by selecting from the ARMOS Main Menu **File / Project / Open** and typing TUTOR in the ARMOS Project Name field. You do not need to specify a database or map name since they are stored in the project record. Select **[Accept]** to continue. If you or someone else has modified the TUTOR project and you want to follow the tutorial, a backup of the TUTOR problem is provided. From the **File / Project / Open** menu, select the "EXBACK" project, then rename it TUTOR using **File / Save As**.

You will not be using all of the ARMOS features in this tutorial. However, this manual describes the alternative features where appropriate. For details on all ARMOS features, please refer to the appropriate section of this manual.

7.1 Description of Example Project

The sample problem involves a gasoline spill

The example problem involves a gasoline leak from an underground storage tank at a service station. Three recovery wells were located on site using the SpillCAD well screening program QFree to optimize recovery and plume control. For two of the recovery wells, the tutorial uses the following X and Y locations: RW-01 located at X=2392.50, Y=2509.50 and RW-03 located at X=2411.75,Y= 2438.40. You will enter each as having six inch casings and you will convert the four inch MW-13 (located at 2312.75, 2498.90) into a six inch recovery well (RW-02). This conversion is accomplished in ARMOS by placing a six inch recovery well at the same location as MW-13.



The CAD base-map covers an area approximately one square mile, but you will set the data and kriging domains to a smaller area near the leak site. To change the data domain, select **Map / Overlay / Setting / Data Domain**. The current coordinate settings are X = -0.5, Y = -0.5 for the lower left corner and X = 5181.85, Y = 5075.65 for the upper right corner. Change the coordinates to X = 2000, Y = 2100 for the lower left corner and X = 2700, Y = 2800 for the upper right corner. Also, change the apparent symbol size to 15, then press **[Accept]** twice.

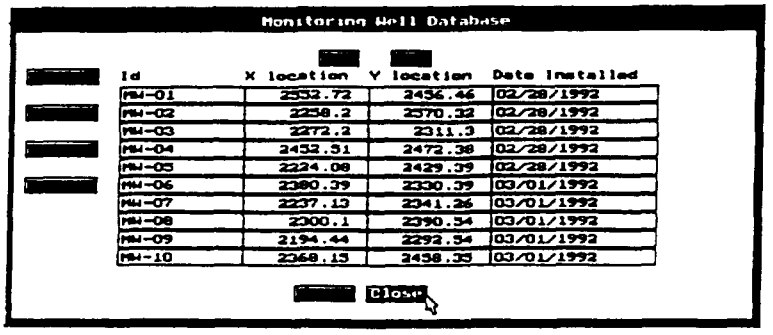
At this point, much of your map is blank. Press the right mouse button for ARMOS to redraw all of the detail in the data domain. You can set ARMOS to automatically redraw the map every time you return to the main menu if you turn on the Automatic Redraw feature– select **Map / Overlay / Setting / Data Domain / Automatic Redraw / [Accept]** and **[Accept]**. Redrawing the map can be time consuming, however, and you may want to leave this option turned off and just use the right mouse button to redraw the map as needed.

To view only the area of the map that you defined as the Data Domain, click on **Map / Zoom / Zoom Reset**. There are nineteen monitoring wells and fifteen soil borings which are displayed as overlays on the map. They can be turned off or on by selecting **Map / Overlay / Setting / Wells / Show Overlay / [Accept] [Accept]**. An X in the box in front of Show Overlay indicates that the overlay is turned on.

You will only need the wells overlay on for this tutorial. Turn off the Soil Borings overlay by selecting **Map / Overlay / Setting / Wells / Show Overlay / [Accept] [Accept]**. The X in the box in front of Show Overlay should now be absent for the Soil Borings overlay.

Fluid level data (depth to water and oil) were taken monthly for all monitoring wells from March through July 1992. Dissolved species concentrations were measured for most wells in April and July 1992. Soil concentration data are available for some monitoring wells and soil boring locations. To view the data, select **Database / Data Entry / Monitoring Wells, Soil Borings, Fluid Level Data, Soil Concentration Data** or **Well Concentration Data / Edit** (Figure 1 shows the Monitoring Wells database).

Figure 1



In addition to the monitoring well and soil boring data, product density and grain size distribution measurements are available. Also, a pump test was performed at the site to determine saturated conductivity and specific yield for the unconfined aquifer.

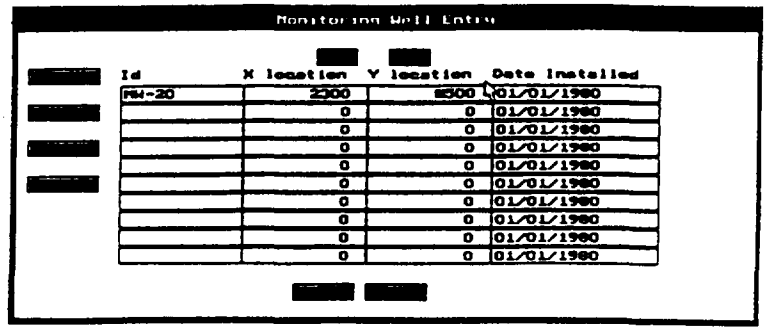
You will perform the following tasks in this tutorial:

- Add data to the database
- Perform a database query and plot the results
- Generate a finite element mesh
- Create an ARMOS input data file
- Run an ARMOS simulation
- Post-process the ARMOS simulation results

7.2 Adding a Monitoring Well

Select **Database / Data Entry / Monitoring Wells / Entry** from the main menu to enter location data for monitoring wells. The tutorial database already includes all of the monitoring wells, but you will add another monitoring well to understand the procedure. In the first blank record, enter **MW-20** for the ID, **2300** for the X-location, and **2500** for the Y-location (Figure 2).

Figure 2

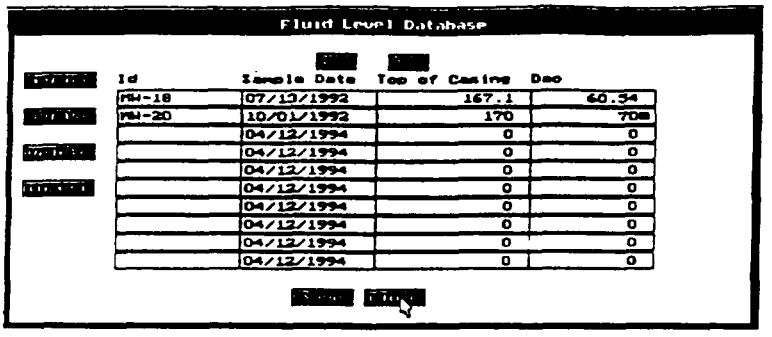


Enter **6/1/92** in the Date Installed field, and **170** in the Top of Casing field. Click on **[Save]** to save this monitoring well.

You need to enter a fluid density for the tutorial, so select **Database / Data Entry / Fluid Level Data / Density**. This brings up the Fluid Density dialog box. Enter 0.73 for the density (of gasoline) and click on **[OK]**.

Now you will enter fluid level data for your new monitoring well. Select **Database / Data Entry / Fluid Level Data / Entry** from the main menu to bring up the Fluid Level Sample Data dialog box. Enter 10/1/92 for the sample date, then press **[Accept]**. A Fluid Level Entry dialog box appears with a listing of all monitoring wells, the sampling date you just input, and the top of casing value for each well. If you had sampled most or all wells on 10/1/92, you would enter the data here. However, since you sampled only MW-20 on that date, it is faster to use an edit screen. Select **[Close]**, then select **Database / Data Entry / Fluid Level Data / Edit**. **[Pg Dn]** to MW-18 (MW-19 exists but has only been used to measure dissolved concentrations– no gauging data for MW-19 is in the database). On the next line, type **MW-20, 10/1/92, 170, 70, 70** (Well ID, Date, Top of casing, Depth to oil, and Depth to water, respectively, see Figure 3). The remaining fields for oil thickness and fluid table elevations will be computed by ARMOS after the screen is saved. Note that for the example well, depth to oil and depth to water are the same because there is no free oil present. If you wanted to save your data, you would select **[Save]**. However, since this is just a practice entry, select **[Close]** to exit without saving the data.

Figure 3



You will enter one more set of data for the new monitoring well, the concentration of benzene found in groundwater sampled on 10/1/92. Select **Database / Data Entry / Well Concentration Data / Edit**. In the blank ID field below MW-19, enter **MW-20**; in the Sample Date field enter **10/1/92**; for the Species enter **benzene**; and in the Concentration field enter **0.0**. Since this is just a practice entry, select **[Close]**.

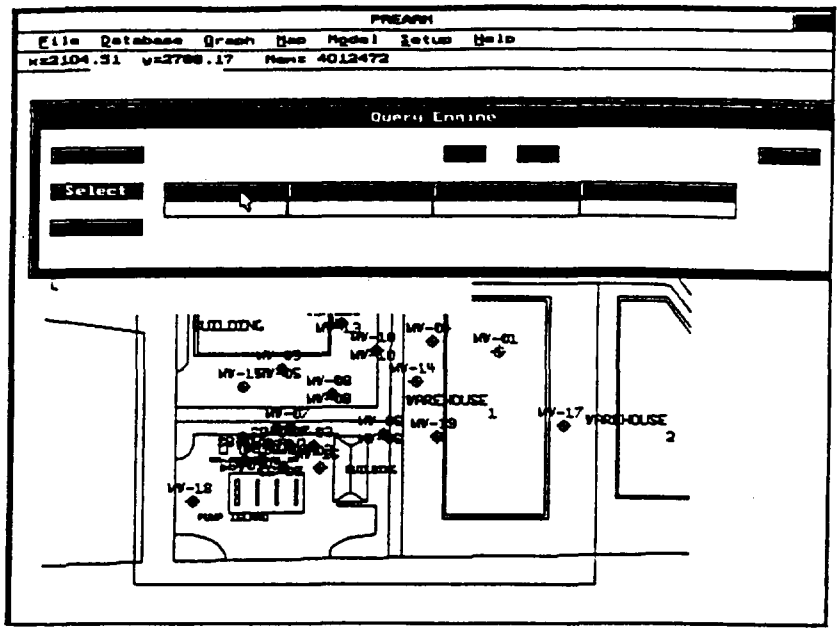
7.3 Querying the Database

7.3.1 Extracting Z_{aw} and H_o data from the database

Select **Database / Query** from the main menu. Inside the Query Engine dialog box, click on **[Select]**. Clicking on each database type toggles its selection (a solid black triangle appears at the left of a selected database). Since you are interested in finding the locations of wells with fluid level measurements, click on **Fluid Levels**. A solid black triangle should now be present at the left of **Locations**, and **Fluid Levels**. Click on **[Done]**.

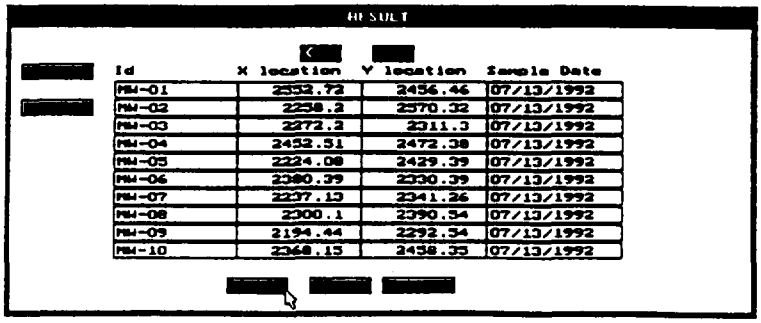
► **Locations**

Figure 4



For this query, you need to know the ID, X-location, Y-location, and Z_{aw}. To set up the query, first Click on **[ID]**, **[X-location]** and **[Y-location]**, and **[Sample Date]** (Figure 4). Under **[Sample Date]** enter **>7/1/92 and <7/31/92** to limit the search to measurements taken in July 1992. Since the **[Zaw]** field is not visible, click on the right pointing arrow until it comes into view. Select the **[Zaw]** field by clicking on the field name. Now execute the **Query**, by clicking on **[Do Query]**. ARMOS will perform the search, and a Result dialog box appears when the **Query** has been completed (Figure 5).

Figure 5



Id	X location	Y location	Sample Date
MW-01	2552.72	2456.46	07/13/1992
MW-02	2258.2	2570.32	07/13/1992
MW-03	2272.2	2311.3	07/13/1992
MW-04	2452.51	2472.38	07/13/1992
MW-05	2224.08	2429.39	07/13/1992
MW-06	2380.39	2330.39	07/13/1992
MW-07	2237.13	2341.26	07/13/1992
MW-08	2300.1	2390.54	07/13/1992
MW-09	2194.44	2292.54	07/13/1992
MW-10	2368.15	2438.35	07/13/1992

In this box you are able to browse the data using the **[Pg Up]**, **[Pg Dn]**, [<], and [>] buttons. If you are satisfied with the results of the **Query**, click on the **[Save]** button to save the **Query** for later manipulation. ARMOS prompts you to enter the query name. Enter

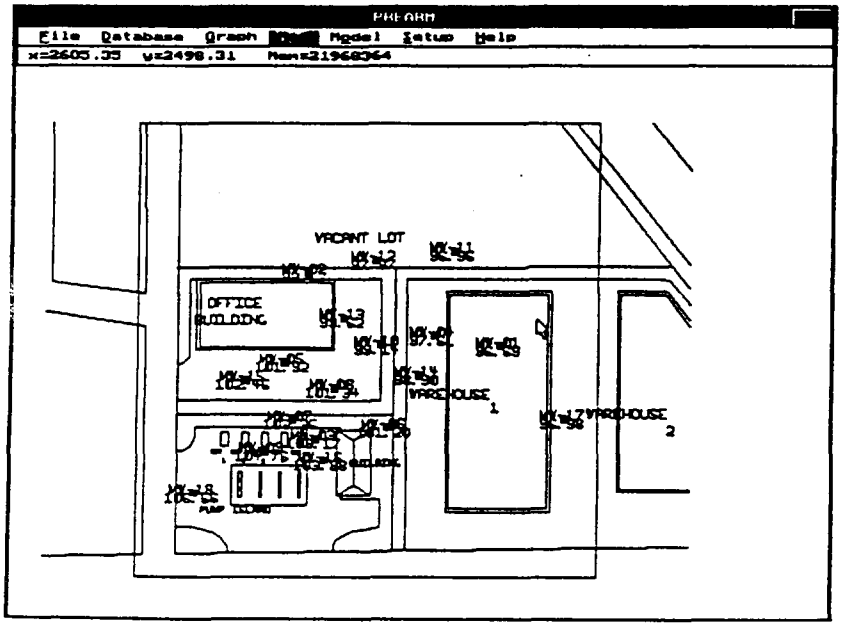
"July Zaw" and click on [**Accept**] to save this **Query**. ARMOS returns you to the Query Engine box, where you can perform another **Query**.

Now, repeat the **Query** procedure above, but select the [**Ho**] field instead of the [**Zaw**] field. Execute the Query by clicking on [**Do Query**]. Name the results "July Ho", then click on [**Accept**]. Click on the [**Close**] button to exit the Query Engine dialog box.

7.3.2 Viewing contours of Z_{aw} and H_o on the basemap

To view the Query results on your map, select **Map / Overlay / Add** from the main menu. The Select Query to Overlay dialog box appears. Click on "**July Zaw**" and "**July Ho**", then [**Done**] to add these Queries to the map. Also, select **Map / Overlay / Setting / July Zaw / [Accept] / [Accept]**. When ARMOS redraws the map, all sampling locations with H_o and Z_{aw} measurements will be shown in red (Figure 6). (You will need to select **Map / Redraw** or click the right mouse button if you are not in Automatic Redraw mode.)

Figure 6



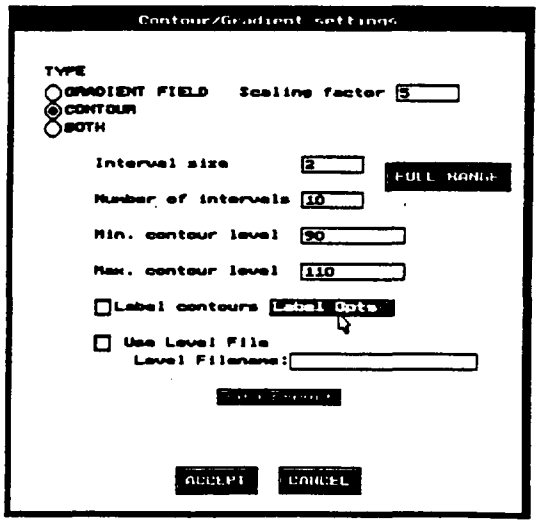
Before viewing the contours of the query results you must first set the domain for the point values to be kriged to. To set the area for the kriging domain select **Map / Overlay / Setting / [Kriging Domain]**. Now set the lower left, and upper right corners of the kriging domain to be the same as the data domain (lower left: 2000,

2100, upper right: 2700, 2800). Set the number of columns and rows both to 29. This will reset the delta x and delta y both to 25 ft.

This spacing will allow you to view the contours on a grid that is close to the final finite element mesh that will be created by following this tutorial. Click on **[Accept]** to save these settings and return to the overlay settings window. The size of kriging domain can be readjusted at any time by using the **Map / Domain / Domain Set** option, and defining a rectangular domain as you would a zoom window.

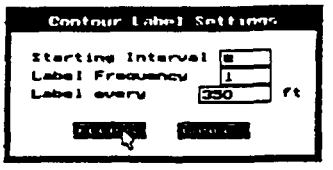
To view contours of Z_{aw}, click on July Zaw. This brings up the July Zaw Overlay Settings dialog box. Click on **Show Contours** under Overlay Method (data points may be shown as posted values, contours, or both). Click on **[Contour Options]**, to bring up the Contour/Gradient settings dialogue box (Figure 7). PreArm automatically sets the contour options to nine intervals over the range of the data. To make the contour interval more aesthetic, change the minimum contour level to 90.0, the maximum contour level to 110.0 and the number of intervals to 10 (the interval size should change to 2). To label the contours click on the Label Contours checkbox so that an X appears in it.

Figure 7



Click on **[Label Opts]** to set the contour labeling options. This will bring up the Contour Labels Settings dialog box (Figure 8). Change the label frequency to 2, and label every to 350 feet.

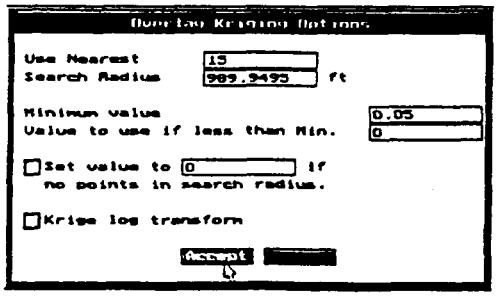
Figure 8



Click on [**Accept**] to accept the Contour Label settings, and then click on [**Accept**] again in the Contour/Gradient settings dialog box to accept and save the changes that were made to the contour settings. This returns you to the July Zaw Overlay Settings dialog box. Before accepting the settings, change the Point Color for this overlay to 1 (blue), so that you can distinguish these contours from the others you will create later. Now click on [**Accept**] to finally accept the settings for the July Zaw overlay. To view the July Zaw contours that were just created click on [**Accept**] to leave the Select Overlay to Adjust Settings dialog box.

Select **Map / Overlay / Settings / July Ho** to adjust the settings for the July Ho overlay. Click on Show Contours. Click on [**Krig Opts**] to set the kriging options for the July Ho overlay (Figure 9). This will bring up the Overlay Kriging Options dialog box. Set the Minimum value to 0.05 and the Value to use if less than Min. to 0.00. These kriging options will help to eliminate "kriging noise" (values greater than zero with no contiguous connection to the body of the plume, and no basis in observed data) from the kriging results.

Figure 9

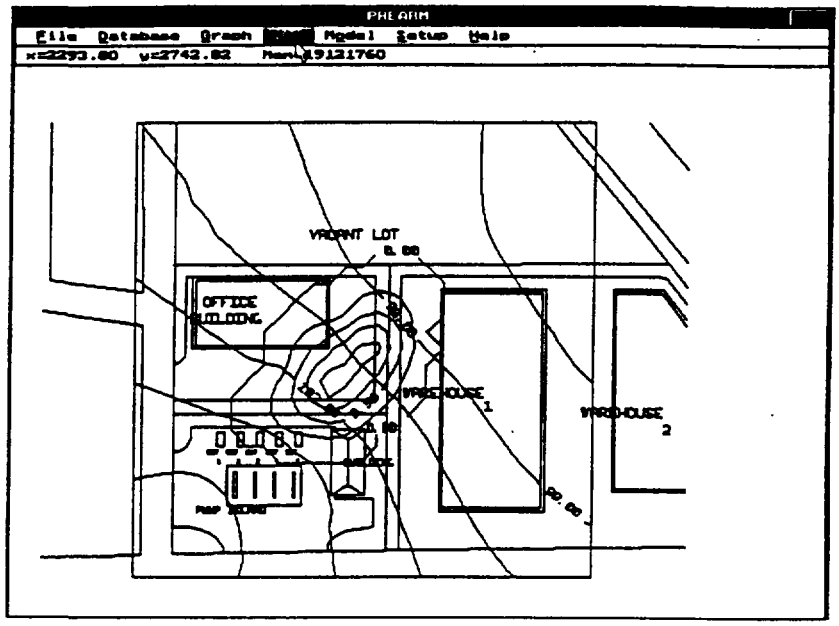


Setting the kriging options becomes particularly important when delineating data with a wide range of values (e.g. contaminant plume outlines), but the default options work well for relatively planar data (e.g. water table). The Krige log transforms option helps to

generate smooth contours when kriging data that has a wide range between the maximum and minimum values (e.g. maximum value and minimum value separated by orders of magnitude).

Press **[Accept]** to use the new kriging options. Now set the **Contour Options** to use a maximum contour level of 2.5 ft with an Interval Size of 0.25 ft. Set the Label Contours box to on and the label frequency under **Label Opts** to 2 (every other contour line) and label every to 350 feet. Click on **[Accept]** until you get back to the base map. ARMOS will now redraw the basemap with the two new contour overlays (Figure 10).

Figure 10

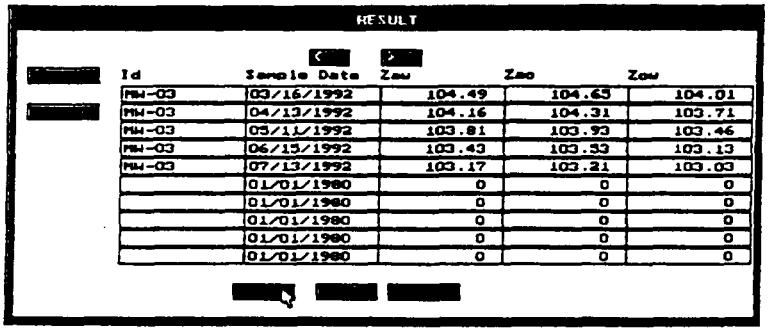


7.3.3 Extracting well fluid elevations vs. time from the database

Select **Database / Query** from the main menu. Click on **[Select]** to select databases for this **Query**. Since your search is concerned only with monitoring well fluid level data, click on Locations to toggle it off. Click on Monitoring Wells and Fluid Levels to include them in the **Query**. Click on **[Done]** to return to the Query Engine dialog box. The fields you are interested in for this query are the ID, Sample Date, Z_{aw} (corrected water table elevation), Z_{ao} (air-oil table elevation), and Z_{ow} (oil-water table elevation). Click on **[ID]**, then click on the box beneath it. Enter **=MW-03**. This instructs ARMOS to extract only data pertaining to monitoring well MW-03. Next,

click on the heading [**Sample Date**]. Click on [>] until the [**Zaw**], [**Zao**], and [**Zow**] buttons appear (air-water, air-oil, and oil-water tables, respectively). Click on each of these headings to include them in the Query result. To perform the Query, click on [**Do Query**]. When the Query has been completed, the Result dialog box appears (Figure 11).

Figure 11



In this box you can browse the data using the [**Pg Up**], [**Pg Dn**], [<], and [>] buttons. Click on [**Save**] to save the **Query** for later manipulation. ARMOS prompts you to enter the Query name. Type **fluid levels for mw-03** and click on [**Accept**]. PreArm returns you to the Query Engine dialog box, where you can perform another Query if desired. Click on [**Close**] to exit the Query Engine dialog box.

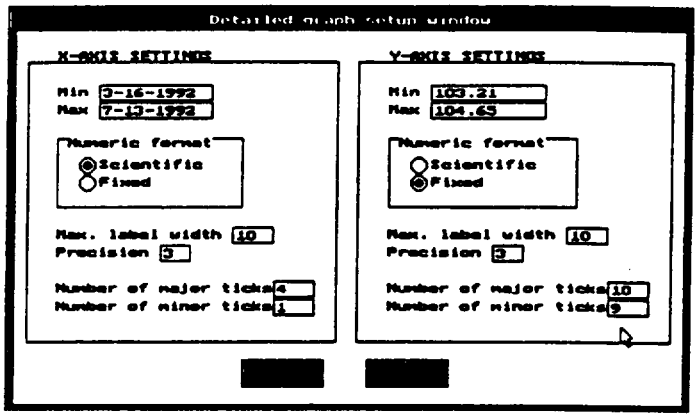
7.3.4 Graphing product and water elevations vs. time

Now you will graph the results of your third Query. Select **Graph** from the main menu, and then click on [**Pick Query**]. In the Select Query to Graph dialog box click on **Fluid levels for MW-03**. ARMOS returns you to the Graph Settings dialog box. Click on the first solid triangle under the X-axis fields heading and select Sample Date. Click on the first solid triangle under the Y-axis fields heading, and select Z_{ao}. Click on the check box to the left of Sample Date to indicate that this series should appear when you view the graph. Click on the second solid triangle under the X-axis fields heading and select Sample Date again. Click on the second solid triangle under the Y-axis fields heading and select Z_{ow}. Click on the check box to the left of the second Sample Date entry to indicate that this series should also appear when you view the graph.

Position the cursor in the Title field and enter the name **Zao and Zow vs. time for MW-03**. Position the cursor in the X-axis label field and enter Date, and in the Y-axis label field enter Elevation (feet).

To view the graph, you could select **[Show]** now and let ARMOS determine the graph setup. However, to present a more aesthetic view, click on **[Manual]** in the Detailed Setup box, and then click on **Setup Details**. This brings up a Detailed graph setup window. In the X-axis Settings box, set the Number of major ticks to 4 and the Number of minor ticks to 1. In the Y-axis Settings box, change the Numeric format to Fixed and the Number of minor ticks to 9 (Figure 12).

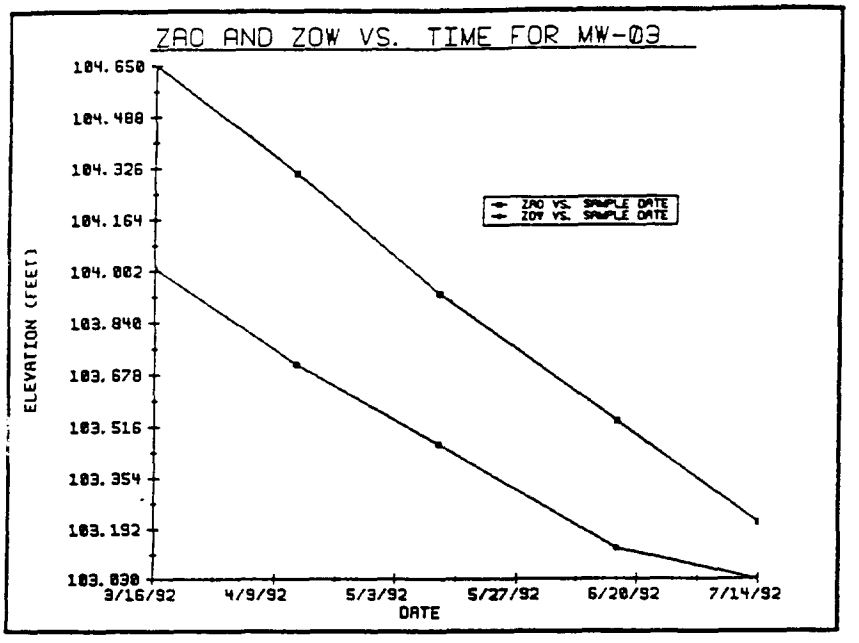
Figure 12



Now press **[Accept]**. When you have returned to the Graph Settings dialog box, press **[Show]** to display your graph.

To move the legend, click anywhere on the graph with the left mouse button and hold the button down. An outline of the legend box appears. Drag this outline to the desired location, and release the mouse button to place the legend. ARMOS redraws the graph with the legend in the new location (Figure 13). Pressing the left Shift key and the left mouse button simultaneously brings up the Detailed Settings box if you want to change settings.

Figure 13



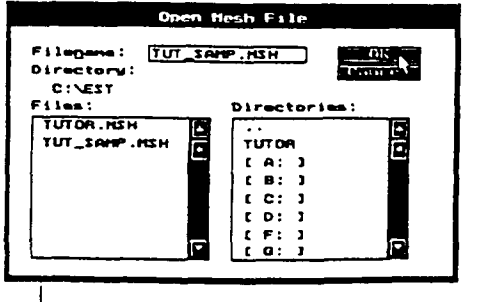
To exit the graph, either press the **<Esc>** key, or click anywhere on the graph with the right mouse button. To exit the Graph Settings dialog box, click on **[Cancel]**.

To turn off your overlays for the next section select **Map / Overlay / Setting / July Zaw**, then toggle off Show Overlay. Do the same for **July Ho**.

7.4 Generating a finite element mesh

7.4.1 Generate Mesh

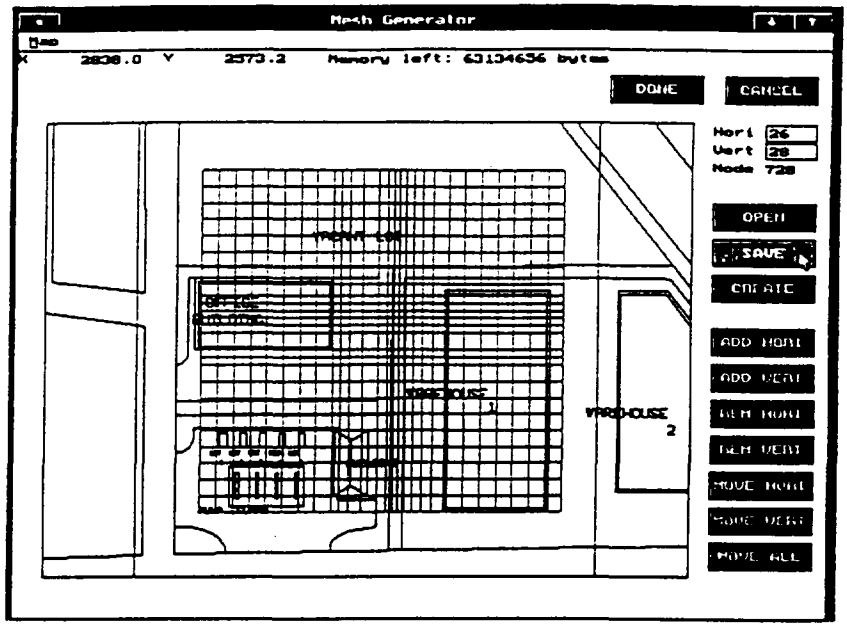
The first step in setting up a finite element simulation is to generate a finite element mesh. The mesh is used to perform calculations and to define spatial distribution of spatially variable parameters. To generate a mesh select **Model / Generate Mesh** from the main ARMOS menu. This brings you to the Mesh Generator screen.



To get a look at what the finished product will be like before you go any further open the mesh-file tut_samp.msh. To do this click on the **[Open]** button. This brings up the file selector dialogue box.

Select the \est\tutor directory and click on the file named tut_samp.msh. Click on [OK].

Figure 14



The [Open] button can also be used to manipulate a previously created mesh file. If a previously created mesh file is used by a previously generated data set, that data set will need to be recreated if the mesh file is modified in any way and saved under the same name.

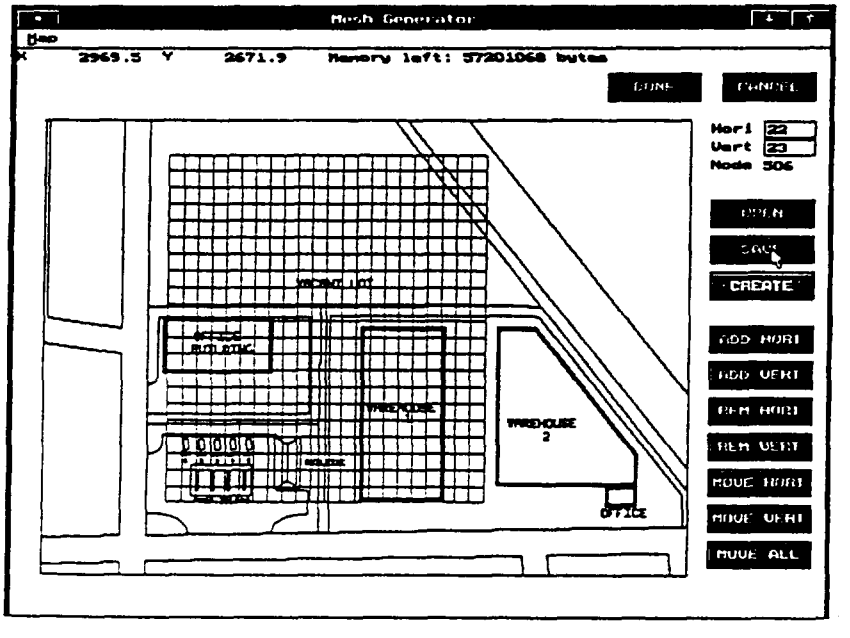
Looking at the tut_samp.msh, notice the areas that have mesh lines closer together (Figure 14). The irregularity of these areas is to place more nodes around the locations of recovery wells to increase the computational accuracy. The finished product of the following exercise should very closely resemble this sample mesh.

The horizontal and vertical spacing of the mesh determines the area represented by each node. Smaller nodal areas yield finer spatial resolution in the simulation output. For this tutorial you will generate a mesh with a horizontal and vertical spacing of approximately 25 feet by 25 feet, with a finer spacing around the proposed recovery wells. From the contours that were created in the previous section you can see that a rectangular domain with corners at lower left: 2100.0, 2200.0, and upper right: 2650.0, 2700.0, encompass the current hydrocarbon plume and allow for a reasonable amount of migration. To use a 25 ft by 25 ft spacing you need 23 vertical lines and 22 horizontal lines.

[Cancel] the tut_samp.msh. Then, to create a new mesh, select **Model / Generate Mesh**. To specify the base number of horizontal and vertical lines in your mesh, type in the two input boxes in the upper right hand corner of the edit window, labelled **Hori** and **Vert**. Place the cursor in the box labeled **Hori,** by clicking in it, and enter 22 for the number of horizontal lines in the mesh. Enter 23 for the number of vertical lines in the mesh in the **Vert** box. The Value listed beside **node** is the total number of nodes that the number of specified horizontal and vertical lines will generate, which in this case is 506 (Figure 15).

After the number of horizontal and vertical lines have been specified, the second step is to define the rectangular boundary for the finite element mesh. Click on **[Create]** and then define the rectangle as you would a zoom box, clicking first on the lower left corner of the domain (approximately 2100, 2200), then dragging the top left corner of the domain box to its desired location (approximately 2650, 2700). This creates the base structure for the mesh (Figure 15).

Figure 15



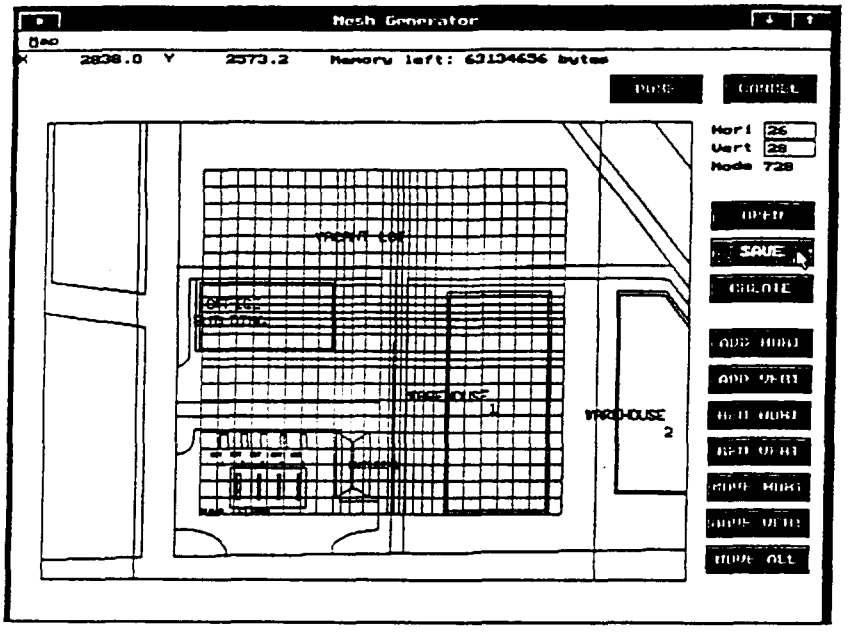
To accommodate the locations of the recovery wells, the mesh must be modified by adding additional horizontal and vertical lines. Nodes need to be located as close as possible to the actual locations of the recovery wells. Placing the additional mesh lines will be much easier if you first zoom in around the recovery well location. The mouse movement translates to smaller map movements when

zoomed in. Select **Map / Zoom / Zoom Area** and define a box (lower left, then upper right) where you will place the recovery wells. You can use the **Pan** function to move around on the map. Click on **[Add Hori]** Place the mouse pointer as close as possible to the location of RW-1 (located at 2392.5, 2498.9) and click. This will add a horizontal mesh line to the mesh. Now Click on **[Add Vert]** and click on the same place on the map. A vertical line is now added to the mesh. The crossing of these two lines will be the location of the of the recovery well.

Repeat the **[Add Hori]** and **[Add Vert]** steps for the two remaining recovery wells (RW-03 located at 2411.8, 2438.4 and RW-02 at 2312.8, 2498.9). Since there is a horizontal mesh line very close to MW-13 (which will be converted to RW-02), there is no need to add a line there. Use the **[Move Hori]** button to slightly adjust the location of the horizontal line near RW-02 so that it directly overlies where RW-02 will be placed.

The mesh spacing around the recovery well locations now needs to be adjusted so that it is more uniform. This can be accomplished by adding more lines, and moving a few others. First add a horizontal line below RW-02, the same distance from it as the line above. Add a horizontal line to the north, and a vertical line to the west of RW-01 in the same fashion as the line that was just added to the west of RW-02. Use **[Move Vert]** to reposition the two vertical lines to the west of RW-01 (2nd and 3rd from RW-01), so that the spacing is more uniform. Move the 2nd horizontal line to the north of RW-01 farther north to even out the spacing of the elements below and above the line. Now add a vertical line just east of RW-03, reposition it and the adjacent line to the east to even out spacing If you were zoomed in, select **Map / Zoom / Zoom Reset** to view the domain with the complete mesh (Figure 16).

Figure 16

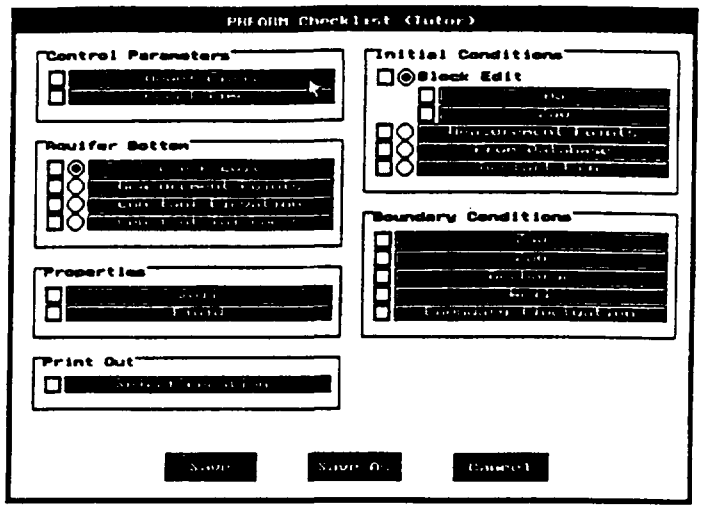


The final number of horizontal and vertical lines in the mesh is now 26 and 28 respectively, with a total of 728 nodes. Now that the mesh design is complete, click on **[Done]**. ARMOS now will prompt you to save your changes, since the mesh has been modified. Save the mesh to **c:\est\tutor\tutor.msh**.

7.5 Creating ARMOS Input Files with the Pre-Processor

To use the Pre-processor for ARMOS (PreArm), select **Model / Pre-processor** from the main menu. Select **New** to open a new file. After you enter a new file name (tutor.arm, in the c:\est\tutor directory) and press **[OK]**, PreArm will prompt you for a mesh file name. Select the mesh that you created in the previous section (tutor.msh, in the c:\est\tutor directory) and press **[OK]**. This brings you to the main checklist screen of the Pre-processor (Figure 17).

Figure 17

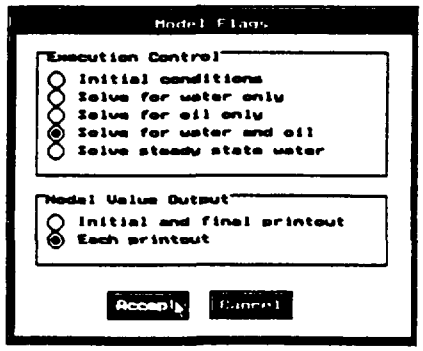


7.6 Control Parameters

7.6.1 Model flags

Set the model flags by selecting **Model Flags** in the **Control Parameters** section of the main checklist screen. Click on the appropriate button to select it.

Figure 18



Set the **Execution Control** to solve for both water and oil equations, so that ARMOS will simulate both oil and water recovery.

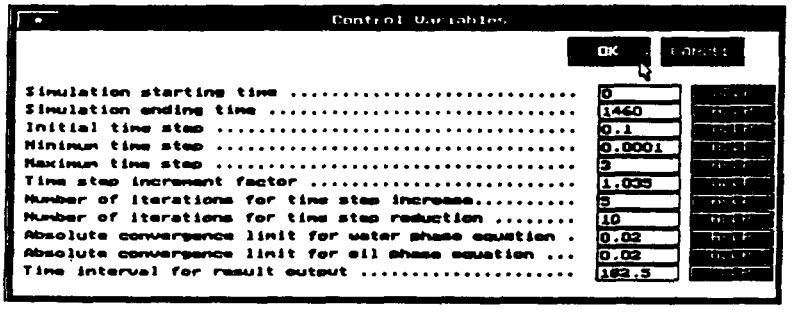
The **Nodal Value Output** switch controls whether nodal values are printed at all printout times or only at initial and final time steps. Setting this option to on will enable you to make contour plots of the simulation results at intermediate intervals.

Select [**Accept**] when these choices are complete (Figure 18) and return to the main checklist dialog box.

7.6.2 Model times

The **Model Times** entry screen prompts you for all input parameters that relate to the simulation time. Enter the values for the model times screen as shown in Figure 19. For information on individual parameters, such as the range of valid values and descriptions of the parameters, use the [**Help**] buttons located to the right of the pertinent field. Setting the Time Interval for Result Output (printout interval) to 182.5 days will allow you to generate contours of simulation results at six month intervals. Click on [**OK**] when all of the parameters have been entered to return to the main checklist.

Figure 19



7.7 Aquifer Bottom Elevation

There are four options available for entering aquifer bottom elevations: block edit, measurement points, constant elevation, and constant aquifer thickness. The constant elevation option will be used in this example problem. For descriptions of these other options, refer to Section 3.5.

Click on the [**Constant Elevation**] button. Enter a value of 70.0 for the elevation of the bottom of the aquifer, and click on [**OK**]. This

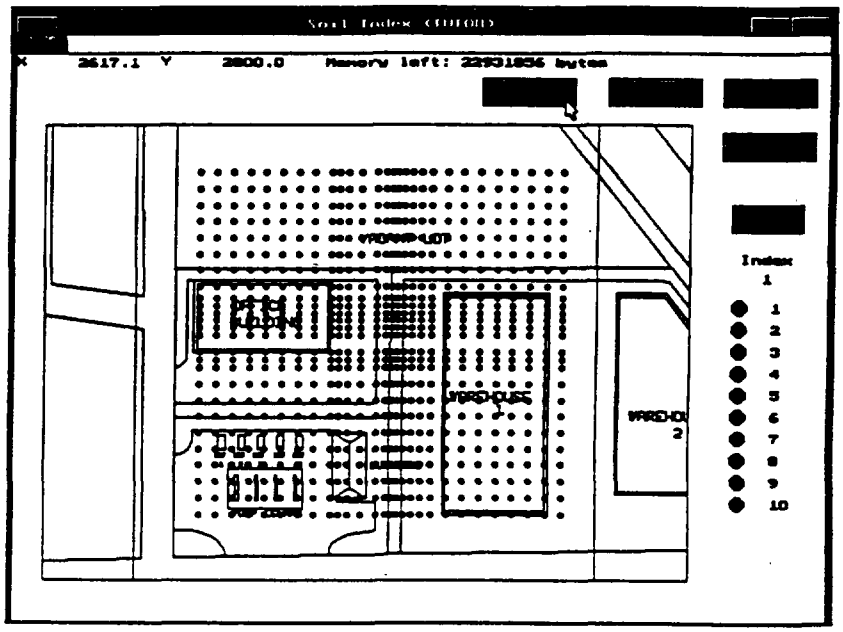
will assign a constant elevation of 70 ft. relative to mean sea level over the entire domain. For spatial variability either the block edit or the measurement points entry options must be used.

7.8 Soil and Fluid Properties

7.8.1 Estimate soil properties

Click on **[Soil]**. This will bring up the Soil Index editor window. This window provides for the discretization of soil index zones, as well as for the entry of the various van Genuchten parameters (Figure 20).

Figure 20



In this tutorial you will use a uniform soil distribution (1 soil index, default = index 1), so defining a spatial distribution will be unnecessary, but to see how the zone editor works you will define a second soil zone and subsequently change it back to is original index of 1.

To define a soil index zone, first click on **[Define]**, then use the left mouse button to click on the corner points of a circumscribing polygon around the area that you want to change, the last point being the same as the first (any shape/ location will do for this demonstra-

tion). Next, click on the desired colored soil index button (number 2 will do) to set the soil index for the defined polygon. Right click the mouse to redraw and view the new soil index distribution. Now change the same zone back to index 1, by defining a zone that encompasses the zone of soil index 2 and click on soil index button 1. To change the index of an individual node, simply click on the node that you want to change, and then click on the desired index.

To enter parameter values for a soil type, select the a node of the soil type to be modified (in the case of the tutor there is only one soil type), and click on **[Edit]**. If you have measured soil properties, the values can be entered into the appropriate fields. More typically, you will not have all of the required data. In this case, ARMOS can help you by providing representative properties for various soils and fluids.

Now you need to enter or estimate the soil properties which include:

- K_{sw} Hydraulic conductivity
- ϕ Total Porosity
- S_m Water saturation at field capacity
- α The mean pore size parameter
- n The pore distribution parameter
- S_{or} Residual oil saturation (saturated zone)
- S_{og} Residual oil saturation (unsaturated zone)
- Ratio Anisotropy ratio
- Angle Anisotropy angle

Select **Estimators** from the file menu. A drop-down menu with six choices appears. As a first approximation for all of the soil parameters, choose **Representative properties for various soils**. Here, ARMOS displays a list of various soil types and their respective parameter values. If you were to select one of these soil types, the values would be inserted in the appropriate fields in the Soil Properties dialog window. For this tutorial, you will not use representative

soil properties. To exit this list without selecting a soil type, click on **[Cancel]**.

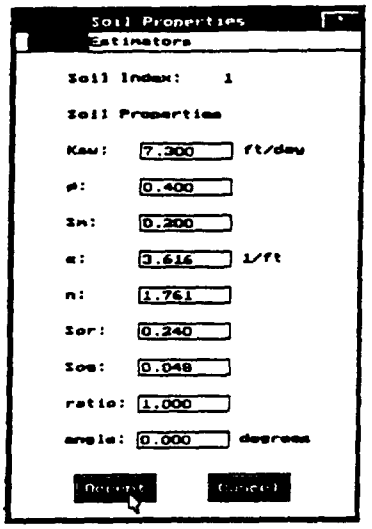
For the tutor problem, hydraulic conductivity (K_{sw}) is 7.30 feet per day measured in a pump test and total porosity (ϕ) is 0.40 as determined from laboratory cores. Enter these values directly by clicking on the respective fields and entering the known values.

Next, return to the **Estimators** menu, and select **Estimators** again. An estimate of S_m can be made from grain size data, but determination from specific yield calculated from a long term pump test is generally preferable. Since you have pump test data, select ***Sm* from specific yield**. Values of total porosity, ϕ, and specific yield, ϕ_e, must be specified. Since you have already entered total porosity as 0.40, you need only enter the specific yield, which is 0.32, as determined by the pump test. Now select **[Solve]** and the program returns the computed value of 0.200 for S_m. Click on **[Accept]** to transfer the value and return to the Soil Properties dialog window.

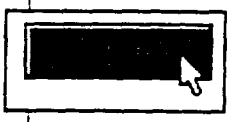
To save some time, enter α as 3.616 and n as 1.761. Click on Help to see definitions of these fields.

Finally, you need to estimate S_{or} and S_{og}. Select **Estimators / Estimation of Sor from Sm**. Setting 3the F-factor to 0.30 and clicking on **[Solve]** yields an estimate for S_{or} of 0.240. Click on **[Accept]** to return to the Properties window. Now select **Estimators / Estimation of Sog from Sm**. Using the S_{og} from S_m estimator with the same F-factor yields 0.048 for S_{og}. Select **[Accept]** to transfer the estimated value to the Soil Properties dialog window (Figure 21). Lastly, enter the ratio of 1.0 (no anisotropy) and 0.0 for the angle.

Figure 21



All of the soil properties have now been entered or estimated. To update the values in the data set, select **[Accept]**.



Now, click on **[Done]** to save the soil properties and the soil index distribution. This will return you to the PreArm Checklist.

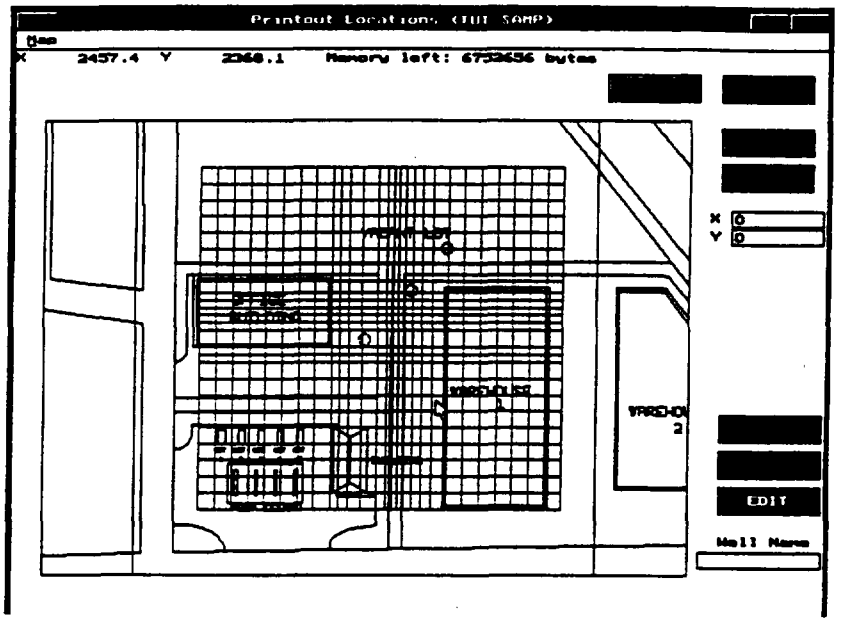
7.8.2 Fluid

Click on **[Fluid]** to enter the Fluid Properties entry screen. For this tutorial a first approximation of the fluid properties can be obtained by selecting **Estimators / Representative properties for various fluids**. A window appears which lists various hydrocarbon fuels and their respective parameter values. Select "gasoline" by clicking the mouse anywhere on the line with gasoline properties. You will be returned to the Fluid Properties window, and representative gasoline properties will be inserted in the Fluid Properties fields. Any of these values can be changed to measured values if they are available. For β_{ao} and β_{ow} PreArm provides estimation routines if you have surface tension data for your fluid or, in the case of crude oil, if you know the crude oil density. The estimation routines are accessed by selecting **Estimators** and then selecting the estimation routine of interest from the dropdown menu. You will not be using these estimators in the tutorial. Click on **[Accept]** to save the fluid parameters that you have entered and return to the PreArm checklist.

7.9 Printout Locations

Click on the **[Select Locations]** button to enter the Printout Locations window (Figure 22). Printout locations can be anywhere inside the kriging domain: they do not have to be on the nodes. Values of state variables like Z_{ao}, Z_{aw}, Z_{ow}, H_o, V_o, etc. (see Chapter 4) are interpolated to those locations and printed out at every printout time. These locations are commonly used to acquire simulation results for monitoring well locations to compare with observed data.

Figure 22



Add a location by clicking on **[Add]**, then clicking on the location on the basemap that you want as a print out location. After selecting a location for output you may enter a "well name" for that location in the box provided. This name will be used by the Post-processor to identify the selected locations. If desired, the x-y location, along with the location "well name" may be edited. Click on **[Accept]** to

enter the location along with its name into the data set. For the tutorial, enter the three following printout locations:

"Well Name"	X Location	Y Location
Obs_loc_#1	2350	2460
Obs_loc_#2	2420	2535
Obs_loc_#3	2475	2600

These three locations can be used to observe plume movement along the path of migration in the simulation results. Now that you have entered the above printout locations, click on **[Done]** to save your data and return to the PreArm checklist.

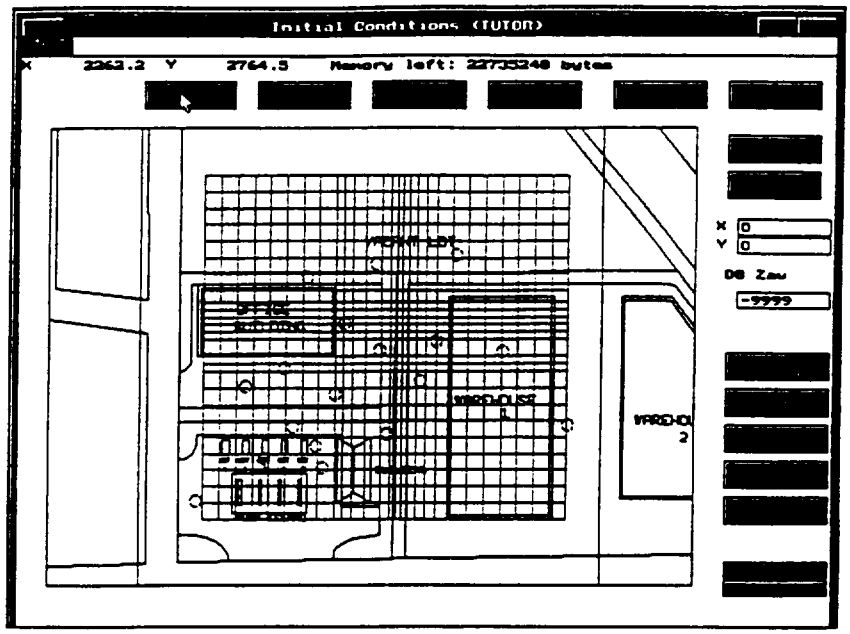
7.10 Initial Conditions

Initial conditions are the fluid table elevations everywhere in the domain at the beginning of the simulation. Initial conditions for the two-phase flow model ARMOS require the air-oil table (Z_{ao}) and air-water table (Z_{aw}) to be specified for all nodes. The program uses Z_{aw} and well oil thickness (H_o) to compute initial Z_{ao} (= Z_{aw} + (1-ρ_{ro}) H_o where ρ_{ro} is the oil specific gravity). There are four options listed in the menu for initial conditions; **1. Block Edit, 2. Measurement points, 3. From database, 4. Restart file.** Use option number 3 **[From Database]** for the tutor problem by clicking on it.

In the Initial Conditions dialog box, click on the **[Method for Ho]** button. The method selected in this dialog box determines how the duplicate points (if any) are handled when retrieved from the database. To generate the initial conditions from the last set of observed values, select the **Last Value** option, and click on **[Accept]**. Repeat this process for Z_{aw}.

Since the selection method is set to last value, PreArm will return the last value over the specified date range. The date for the last measurement taken falls within the default date range, therefore the date criteria do not need to be reset. Now use the **[Get]** button to retrieve the information from the database. After the search for both Z_{aw} and H_o data is complete you will be brought to the initial conditions editing window (Figure 23).

Figure 23



Click on **[Grid Zaw]** to contour Z_{aw} from the current set of data points, and **[Grid Ho]** to contour H_o from the current set of data points. After gridding, right click the mouse in order to see the contours of the data.

Now set the kriging options for H_o as you did in Section 7.3.2, by clicking on **[Ho Opt]**. Set the minimum value to 0.05 and the value to use if less than minimum to 0.0. You can use the defaults for Z_{aw} so skip over **[Zaw Opt]**. You now need to re-grid H_o since the kriging options have changed since the last time H_o was gridded. Click on **[Grid Ho]**, then right click the mouse to view the new H_o contours.

There are two categories of data points used in generating initial conditions:

1) Database points - Z_{aw} or H_o points that are retrieved from the database. **[DB Zaw]** - database Z_{aw} shows all locations for data points with values that fall within the specified date range. **[DB Ho]** - database H_o shows all locations for data points with values that fall within the specified date range.

2) Control points - Control points are used to fill in data gaps for kriging. These points allow the user to specify values for areas where there is no data or where measurements in some wells were not performed during the selected date range. Sometimes control

points are necessary for the kriging algorithm to generate rationally distributed contours. For example, a well without any historical occurrence of hydrocarbon was not sampled during the specified time period. A control point with $H_o = 0$ could be added at the well location to reflect this. **[Ctrl Zaw]** - shows all locations for Z_{aw} control points. **[Ctrl Ho]** - shows all locations for H_o control points.

The **[Add]**, **[Remove]**, and **[Edit]** functions work on all four types of data points. Adding or editing of points must be followed by clicking on the **[Accept]** button to enter the data modifications into the data set. For the tutor problem the data that was retrieved from the database produces contours which appear acceptable without the addition of control points. Click on **[Done]**, this will exit the initial conditions screen, save your changes, and return you to the Pre-Arm Checklist.

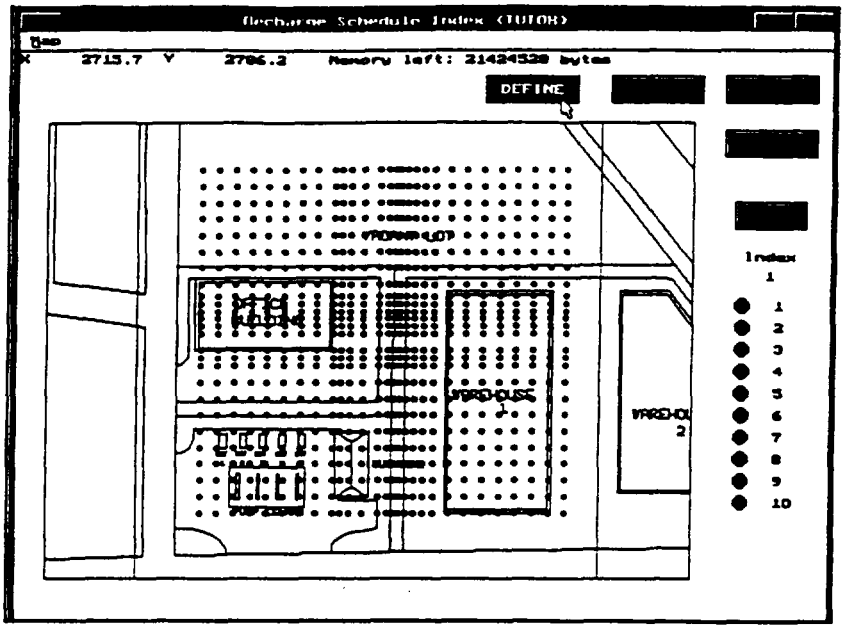
7.11 Boundary Conditions

ARMOS employs boundary condition schedules as a simple and flexible means of specifying time varying values for elevations and flow rates. There are five different types of boundary conditions that can be used in a simulation. The first two, Z_{aw} and Z_{ao} will not be used for the tutor problem. They are used to fix Z_{aw} and Z_{ao} fluid elevations with respect to time at specified nodes within the domain, and are discussed in Section 3.9.1 and 3.9.2. The last three; **Recharge**, **Wells**, and **Boundary fluctuation** will be used.

7.11.1 Recharge

Click on **[Recharge]** to bring up the nodal editor for recharge indexes (Figure 24).

Figure 24



The nodal editor for recharge indexes functions in the same fashion as the soil index editor (Section 7.8.1). At the tutor site there is high degree of evapotranspiration, and little annual precipitation. These conditions make for negligible net recharge to the water table, therefore a net recharge of 0.00 ft^3/day will be used. Click on a node to select Index 1. Next, click on **[Edit]** to define the recharge versus time schedule (see Section 3.9.3 for a description of schedules). Enter the values shown below, then click on **[OK]**.

Time (day)	**Rate (ft/day)**
0	0
99999	0

To save the schedule and index distribution, click on **[Done]**. This will return you to the PreArm Checklist.

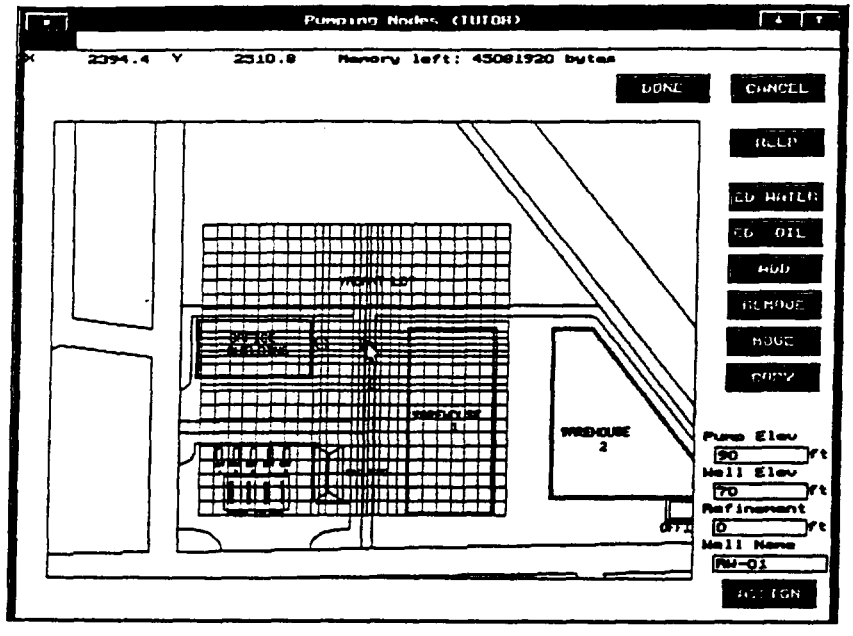
7.11.2 Well

A well node is a mixed-type internal boundary node. Well node boundary conditions are defined by schedules of specified flow rates (cubic feet per day) on interior nodes versus time. For a dis-

cussion of how well nodes are applied, and the relevant pumping node options, see Section 3.9.4.

Click on **[Well]** to enter the Pumping Nodes window (Figure 25).

Figure 25



Now use the **Map / Zoom / Zoom Area** function to zoom in to an area that encompasses the discretized mesh for recovery wells. You may first want to turn off the **Initial Zaw** and **Initial Ho** overlays by selecting **Map / Overlay / Setting** and clicking on **Initial Zaw**. Select **Contour Settings** and remove the **X** in the **Show Contours** box. Select **[Accept]** and **[Accept]** to return to the Select Overlay to Adjust Settings dialog box. Then turn off the **Initial Ho.** The three recovery wells mentioned in Section 7.1 now need to be added to the data set. The three recovery wells need to be located at the following coordinates:

Well Name	X Coordinate	Y Coordinate
RW-01	2392.50	2509.50
RW-02	2312.75	2498.90
RW-03	2411.75	2438.40

Click on **[Add]** then click on the location of RW-01. In the Water Rate Schedule window enter the following pumping schedule for the water phase:

Time (Days)	**Rate (ft^3/day)**
0	0
1	288.7
99999	288.7

The above schedule gradually turns on the pump over the first day of the simulation and maintains it at a constant rate after the first day. Ramping the rate over the first day reduces nonlinearity of the solution. Click on **[OK]** to save this schedule and proceed to the oil pumping schedule.

The actual oil pumping rate is governed by the maximum rate that oil can flow to the well. If this rate exceeds the specified oil pumping rate, the specified oil pumping rate is used. If the specified pumping rate is greater than the rate at which oil can flow to the well, ARMOS automatically uses the lower rate (i.e., oil cannot be removed from a well faster than it can be replaced). Usually a rate that is somewhere around 10 percent of the pumping rate should suffice. Enter the following values for the oil rate schedule and then click on **[OK]**.

Time (Days)	**Rate (ft^3/day)**
0	0
1	28.8
99999	28.8

This will return you to the Pumping Nodes dialog box. Click on the well node that you have just specified (the node should become highlighted), then place the cursor in the Pump Elev box. Enter a value of 75 in this box. This is the elevation of the pump in the well. The next box, Well Elev, is the elevation of the bottom of the well screen. Enter a value of 70 in this box. Due to the nonlinearity of the system surrounding a pumping node, ARMOS employs an automatic mesh refinement scheme for pumping nodes. You specify the spacing of refinement in the Refinement box. Enter a value of 5 in this box. In the Well Name dialog box, enter the appropriate well

name, and click on [**Assign**]. This will update parameters for this well.

Now, repeat the above process for the two remaining recovery wells, using the same pumping schedules and well parameters. The [**Copy**] option may be used to duplicate well information, however be cautious when using the copy option, since this option does not create a separate schedule for the copied wells. Copied wells actually share the same schedule. If you are certain that wells will always use the same pumping rates, you can use this option. Click on [**Done**] to save the pumping node information and return to the PreArm dialog box.

7.11.3 Boundary Node Fluctuation

Click on [**Boundary Fluctuation**] to enter the fluctuation schedule for boundary nodes. For discussion on how boundary schedules are applied, see Section 3.9.5. Enter the following schedule for the boundary nodes.

Time (day)	**Fluctuation (feet)**
0	0
99999	0

Now click on [**OK**] to save the schedule and return to the Pre-processor dialog box. This schedule will hold the boundaries of the model to their initial values over the duration of the schedule (from 0 to 99999 days).

You have now completed entering all the parameters that ARMOS needs to perform a simulation. Click on [**Save**] to exit the Pre-processor. The message, "Kriging Zaw and Ho" will be displayed as ARMOS interpolates the initial conditions to the finite element mesh, saves the dataset and returns to the main menu.

7.12 ARMOS Run Module

After you have completed the Pre-processor checklist, choose **Model / Run** from PreArm. Click on [**Select**]. ARMOS will prompt you for a file name via the file selector dialog box. After

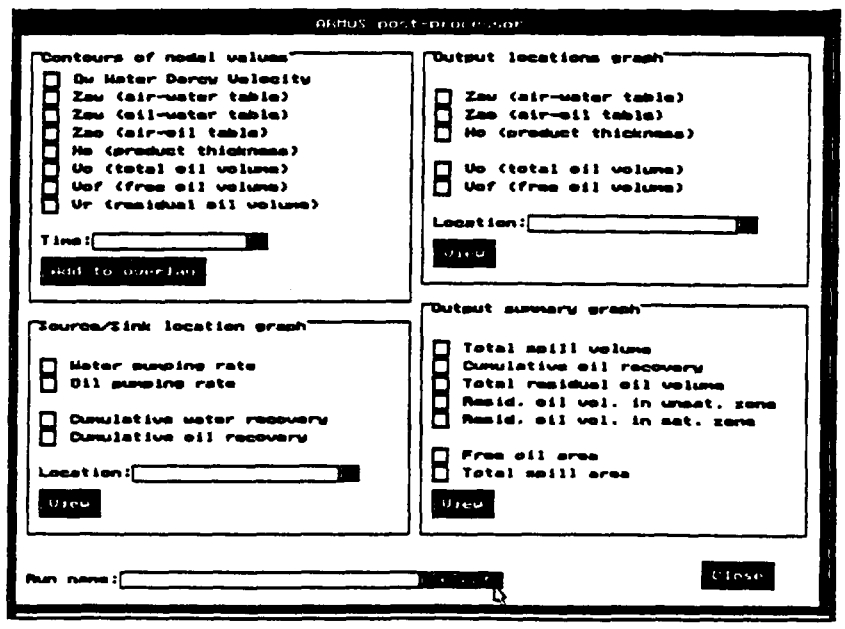
you have entered a name, click on **[Run]**. PreArm will now instruct you to leave the Pre-processor and run the ARMOS main module. To run ARMOS from Windows®, minimize the Pre-processor , and double-click the RunArm icon from the ES&T group in Windows®. To run ARMOS from DOS, exit the Pre-processor and type **armos5** at the DOS prompt.

Both DOS ARMOS and RunArm will execute the last data set selected with the **Model / Run** option. Because RunArm is a true Windows® application, it may be minimized to run in the background while you work on something else.

7.13 ARMOS Post-processor

After the run is complete, return to PreArm and select **Model / Post-processor** from the main menu. The ARMOS Post-processor menu will appear (Figure 26). The Post-processor allows you to contour and graph the results of your ARMOS run. Click on **[Select]**, and select tutor.oof in the **est\tutor** directory.

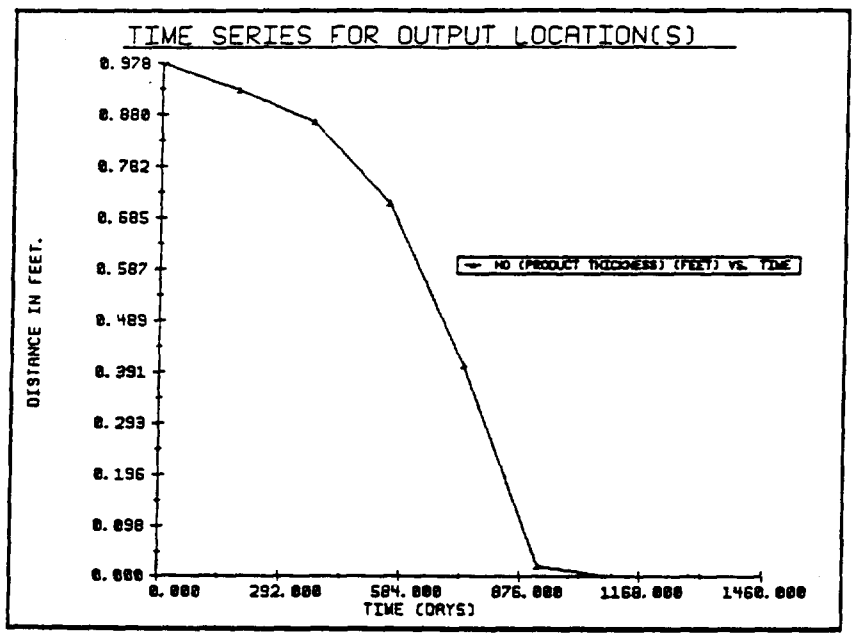
Figure 26



We will demonstrate just a few of the Post-processor capabilities in this section. Feel free to try others after following the tutorial examples.

Click on the box in front of **Ho (product thickness)** under **Output locations graph.** An X will appear in the box next to this selection. Click on the [v] button next to the **Location:** box and select the location named obs_loc_#1. Then click on **[View].** The X-Y graph of H_o vs. time at this well should then appear. To adjust the set up and/or print the graph hold down the left shift button and click the left mouse button. This will bring up the Detailed Graph Setup window. Set the Numerical format on both axes to use a Fixed format with the precision set to 0 for the x-axis only. Click on **[Accept]** to use the new settings. The graph should now appear as in Figure 27.

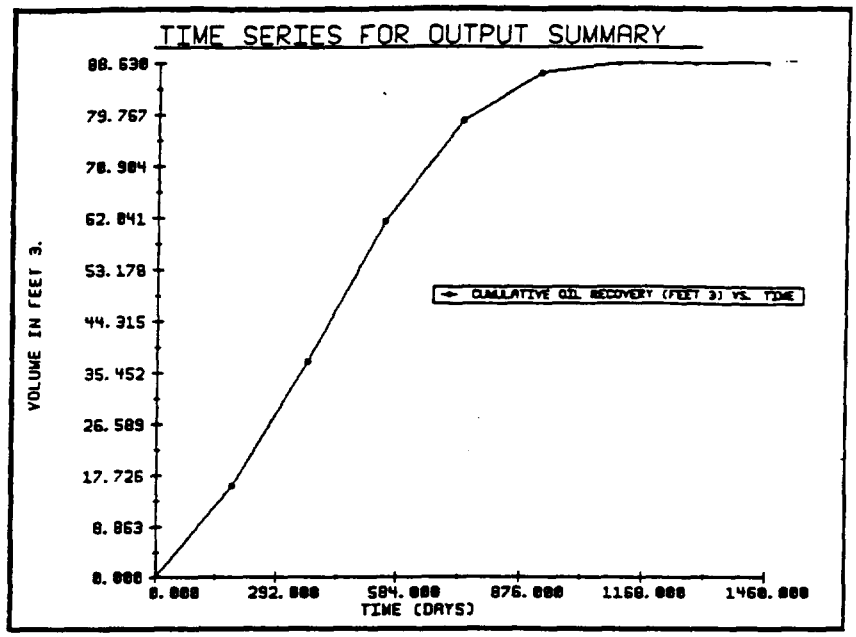
Figure 27



Hit **<Esc>** to return to the Post-processor window.

Next click on **Cumulative oil recovery** in the **Output summary graph** option. An X should appear in the checkbox. Click on [View], and once again use the left shift/left mouse click to set the graph settings as you did for the H_o vs. time graph. Use the same settings for this graph also. It should appear as in Figure 28.

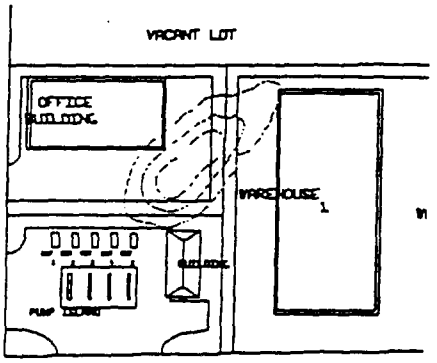
Figure 28



Hit the **<Esc>** key to return to the Post-processor window.

Now click on the **Vr (residual oil volume)** selection under the **Contours of nodal values** section. Nodal data are available at print out times only because you turned on the switch for nodal output in the Pre-processor. Otherwise, contour plots would only be available at the initial and final time steps. Click on the [v] button and select the final output time (1460). Now click on the **[Add to overlay]** button to add the contours of V_r to the overlays. This will generate contours of the residual oil volume at the end of the simulation. (While you are in the Post-processor you cannot view the contours.) You may add as many different overlays as you like. They will be placed on the basemap once the Post-processor is closed. Click on **[Close]** to exit the Post-processor and return to the main window. You may now access **Map / Overlay / Settings** to select the Vr (residual oil volume) at: 1460. Select [Accept], [Accept] when the Contour/Mesh Settings window appears to use the default options for this overlay. The default options will produce the contours shown in Figure 28.

Figure 29



You have now successfully completed the tutorial in this chapter. Feel free to examine the other features of the Post-processor. To exit the ARMOS Pre-/Post-processor, select **File / Exit**.

8. References

Abriola, L. M., and G. F. Pinder, A multiphase approach to the modeling of porous media contamination by organic compounds, 2, Numerical simulation, Water Resour. Res., 21, 19-26, 1985.

American Petroleum Institute, A Guide to the Assessment and Remediation of Underground Petroleum Releases, second ed., August 1989.

Baker, O. and W. Swerdloff, Finding surface tension of hydrocarbon liquids, Oil and Gas J., 125, Jan 2, 1956.

Brooks, R. H. and A. T. Corey, Hydraulic properties of porous media, J. Irrig. Eng. Div., Am. Soc. Civil Eng., 92, 61-88, 1966.

ES&T, 1990, MOTRANS Version 1.2, Environmental Systems & Technologies, Inc., 57 p.

ES&T, 1990, SOILPROP A Program to Estimate Unsaturated Soil Hydraulic Properties from Particle Size Distribution Data, Version 2.0, Environmental Systems & Technologies, Inc., 57 p.

Faust, C. R., Transport of immiscible fluids within and below the unsaturated zone A numerical model, Water Resour. Res., 21, 587-596, 1985.

Harr, M. E., Groundwater and Seepage, McGraw-Hill, New York, 1962.

Hockmuth, D. P. and D. K. Sunada, Ground water model of two phase immiscible flow in coarse material, Ground Water, 23, 617-626, 1985.

Huntley, D. and R. N. Hawk, Non-aqueous phase hydrocarbon saturations and mobility in a fine-grained, poorly consolidated sandstone, Proc. Petrol. Hydrocarbons and Organic Chemicals in Groundwater, NGWA, Houston, November 1992.

Kaluarachchi, J. J., J. C. Parker and R. J. Lenhard, Modeling flow in three fluid phase porous media with nonwetting fluid entrapment,

Proc. Conf. Subsurface Contamination by Immiscible Fluids, Calgary, Cananda, 1990a.

Kaluarachchi, J. J. and J. C. Parker, An efficient finite element method for modeling multiphase flow in porous media, Water Resour. Res., 25, 43-54, 1989.

Kaluarachchi, J. J., J. C. Parker and R. J. Lenhard, A numerical model for areal migration of water and light hydrocarbon in unconfined aquifers, Adv. Water Resour., 13, 29-40, 1990b.

Kaluarachchi, J. J., J. C. Parker and R. J. Lenhard, A numerical model for areal migration of water and light hydrocarbon in unconfined aquifers, Adv. Water Resour., 13, 29-40, 1990.

Kaluarachchi, J. J. and J. C. Parker, Multiphase flow in porous media with a simplified model for oil entrapment, Transport in Porous Media, 7, 1-14, 1992.

Katyal, A. K., J. J. Kaluarachchi and J. C. Parker, Evaluation of methods for improving the efficiency and robustness of multiphase flow equations, In: K. U. Weyer (ed.), Subsurface Contamination by Immiscible Fluids, Balkema, Rotterdam, p. 203-209, 1992.

Kemblowski, M. W. and C. Y. Chiang, Hydrocarbon thickness fluctuations in monitoring wells, Ground Water, 28, 244-252, 1990.

Kool, J. B. and J. C. Parker, Analysis of the inverse problem for transient unsaturated flow, Water Resour. Res., 24, 817-830, 1988.

Kozeny, J., Theorie und Berechnung der Brunnen, Waseskraft und Wasserwirtschaft, 8-10, 1933.

Land, C. S., Calculation of imbibition relative permeability for two- and three-phase flow from rock properties, Trans. Am. Inst. Min. Metall. Pet. Eng., 243, 149-156, 1968.

Lenhard, R. J., J. C. Parker and J. J. Kaluarachchi, A model for hysteretic constitutive relations governing multiphase flow, 3. Refinements and numerical simulations, Water Resour. Res., 25, 1727-1736, 1988b.

Lenhard, R. J. and J. C. Parker, Estimation of free hydrocarbon volume from fluid levels in observation wells, Ground Water, 28, 57-67, 1990.

Martin, J. C., Partial integration of equations of multiphase flow, Soc. Petrol. Eng. J. 370-380, 1968.

Mercer, J. W. and R. M. Cohen, A review of immiscible fluids in the subsurface: properties, modesl, characterization and remediation, Contaminant Hydrology, 6, 107-163, 1990.

Mishra, S., J. C. Parker and N. Singhal, Estimation of soil hydraulic properties and their uncertainty from particle size distribution data, J. Hydrol., 108, 1-18, 1989.

Mishra, S., J. C. Parker and N. Singhal, Estimation of soil hydraulic properties and their uncertainity from particle size distribtuion data, J. Hydrol., 108, 1-18, 1988.

Osborne, M. and J. Sykes, Numerical modeling of immiscible organic transport at the Hyde Park landfill, Water Resour. Res., 22, 25-33, 1986.

Ostendorf, D. W., R. J. Richards and F. P. Peck, LNAPL retention in sandy soil, Ground Water, 31, 285-292, 1993.

Parker, J. C., R. J. Lenhard, and T. Kuppusamy, A parametric model for constitutive properties governing multiphase flow in porous media, Water Resour. Res., 23, 618-624, 1987.

Parker, J. C. and R. J. Lenhard, Vertical integration of three phase flow equations for analysis of light hydrocarbon plume movement, Transport in Porous Media, 5, 187-206, 1989

Parker, J. C., R. J. Lenhard and T. Kuppusamy, A parametric model for constitutive properties governing multiphase flow in porous media, Water Resour. Res., 23, 618-624, 1987.

Parker, J. C., J. J. Kaluarachchi, V. J. Kremesec and E. L. Hockman, Modeling free product recovery at hydrocarbon spill sites, Proc. Petrol. Hydrocarbons and Organic Chemical in Groundwater, NWWA, 1990.

Parker, J. C., J. L. Zhu, T. G. Johnson, V. J. Kremesec and E. L. Hockman, Modeling free product migration and recovery at hydrocarbon spill sites, Ground Water, Vol. 32, No. 1, Jan. - Feb. 1994.

van Genuchten, M. Th., A closed-form equation for predicting the hydraulic conductivity of unsaturated soils, Soil Sci. Soc. Amer. J., 44, 892-898, 1980.

Weiss, G. (ed), Hazardous Chemicals Data Book, Noyes Data Corp., Park Ridge, NJ, p. 485, 1980.

Appendix A Specifications for Mesh Files

The numerical mesh for ARMOS is defined by a file that gives coordinates of all nodes and connecting of the elements. The mesh may consist of any combination of triangular and quadrilateral elements. The file extension **must** be in the form ***.msh** to be compatible with ARMOS. The file format is as follows:

Line no.	Variable name	Format	Description
1	NN	I5	Number of nodes in mesh
	NEL	I5	Number of elements in mesh
2	XCOORD(I)	F12.2	X coordinate of node I
	YCOORD(I)	F12.2	Y coordinate of node I
3... NN+1	Repeat line 2, NN-1 times (for all nodes)		
NN+2	N1(J)	I5	Node 1 of element J
	N2(J)	I5	Node 2 of element J
	N3(J)	I5	Node 3 of element J
	N4(J)	I5	Node 4 of element J (zero for triangular element)
NN+3... NN+NEL+1	Repeat line NN+2, NEL-1 times (for all elements)		
NN+NEL+2	Meshend = 0	I5	0 for end of file marker on last line of mesh file

Note: "Node numbers" are global node numbers corresponding to local node numbers 1-4 which are labeled counterclockwise around element.

Appendix B *.ELE and *.IMP Files

Specifications for *.ELE Files

This file format is used for importing an ASCII file into the measurement points section under the bottom elevations heading in the pre-processor checklist.

Line no.	Variable name	Format	Description
1	NPTS	I5	Number of data points in file
2	XCOORD(I)	F12.2	X coordinate of point I
	YCOORD(I)	F12.2	Y coordinate of point I
	ZELEV(I)	F10.4	Elevation of point I
3... NPTS +1	Repeat line 2, NPTS-1 times (for all points)		

Specifications for *.IMP Files

This file format is used for importing ASCII monitoring well data into the measurement points section under the initial conditions heading in the pre-processor checklist.

Line no.	Variable name	Format	Description
1	NWELL	I5	Number of well data points in file
2	XCOORD(I)	F12.2	X coordinate of well I
	YCOORD(I)	F12.2	Y coordinate of well I
	Zaw(I)	F10.4	*Water table potentiometric surface elevation in well I
	Ho(I)	F10.4	*Hydrocarbon thickness in monitoring well I
3... NWELL+1	Repeat line 2, NWELL-1 times for (all well data points)		

* A value of ***-9999.0*** entered for either Z_{aw} or H_o is ignored by the interpolation algorithm. This facility allows you specify only one type of data for interpolation at any well data point location, neglecting the other.

Appendix C Description of ARMOS 5.0 Main Input

Line	Variable	Format	Description
0	BLANK LINE		
1	Title	72A1	Description or title of the problem
2	IEXEC	I5	Index for solution options and execution control = 0 prints input and initial conditions = 1 solves transient water flow only = 2 solves transient oil flow only = 3 solves transient water and oil flow = 4 solves steady state water
	IDIM	I5	Index to specify linear dimension = 0 feet = 1 meters
	IMASS	I5	Oil mass balance correction option = 0 no mass balance correction = 1 mass balance correction done
	IGRAF	I5	Run time screen graphics option = 0 no screen graphics = 1 plot screen graphics
	NODP	I5	= 0 nodal results printed at initial and final time steps = 1 nodal results printed at all printout time intervals
3	STIME	F10.4	Simulation starting time
	ETIME	F10.4	Simulation ending time
	DELT	F10.4	Starting time step (ca. 0.001-0.1 day)
	DETMI	F10.4	Minimum time-step size (usually = DELT)
	DETMX	F10.4	Maximum time-step size (usually 1-10 for oil flow)
	DETRA	F10.4	Time step increment factor
	DPRIN	F10.4	Time interval for results printouts
4	ITRMI	I5	Maximum iterations for time step increase (ca. 3-4)

Line	Variable	Format	Description
	ITRMX	I5	Number of iterations for time step reduction (ca. 6-10)
	ABSW	F10.4	Absolute convergence limit for water phase head (ca. 0.01-0.05)
	ABSO	F10.4	Absolute convergence limit for oil phase head (ca. 0.01-0.05)
0	BLANK LINE		
0	BLANK LINE		
11	NMAT	I5	Number of soil types (max=10)

Line 12 should be repeated NMAT times for each soil type I

12	PROP(I,1)	F10.4	Mean pore size parameter, α (1/L)
	PROP(I,2)	F10.4	Water saturation at field capacity, S_m
	PROP(I,3)	F10.4	Pore distribution parameter, n
	PROP(I,4)	F10.4	Total porosity, ϕ
	PROP(I,5)	F10.4	Mean saturated conductivity, $\overline{K}_{sw}$ (L/T)
	PROP(I,6)	F10.4	Saturated zone residual oil saturation, S_{or}
	PROP(I,7)	F10.4	Unsaturated zone residual oil saturation, S_{og}
	PROP(I,8)	F10.4	Max/min anisotropy ratio, R
	PROP(I,9)	F10.4	Anisotropy angle, ω (degrees)
0	BLANK LINE		
14	DENR	F10.4	Ratio of oil to water density, ρ_{ro}
	VISR	F10.4	Ratio of oil to water viscosity, η_{ro}
	BAO	F10.4	Air-oil scaling parameter, β_{ao}
	BOW	F10.4	Air-oil scaling parameter, β_{ow}
0	BLANK LINE		

Line 20 is entered only if INIT = 3

20	RESTART	A12	Name of a restart file
0	BLANK LINE		
21	NZAW	I5	Number of specified Z_{aw} nodes

Line	Variable	Format	Description
Line 22 is entered only if NZAW >0 and is repeated NZAW times			
22	IZAW(I,1)	I5	Node number of specified Z_{aw} node
	IZAW(I,2)	I5	Schedule number of specified Z_{aw} node
23	NFLUC	I5	Schedule number for water table fluctuation = 0 no water table fluctuation > 0 boundary node Z_{aw}'s fixed at initial values plus a fluctuation given in schedule NFLUC
24	NZAO	I5	Number of specified Z_{ao} nodes
Line 25 is entered only if NZAO >0 and is repeated NZAO times			
25	IZAO(I,1)	I5	Node number of specified Z_{ao} node
	IZAO(i,2)	I5	Schedule number for the specified Z_{ao} node
26	NQW	I5	Number of specified water flux nodes
Line 27 is entered only if NQW >0 and is repeated NQW times			
27	IQW(I,1)	I5	Node number of specified water flux node
	IQW(I,2)	I5	Schedule number for specified water flux node
28	NQO	I5	Number of specified oil flux nodes
Line 29 is entered only if NQO >0 and is repeated NQO times			
29	IQO(I,1)	I5	Node number of specified oil flux node
	IQO(I,2)	I5	Schedule number for the oil water flux node
30	NRECH	I5	Number of specified water recharge nodes
Line 31 is entered only if NRECH > 0 and is repeated NRECH times			
31	IRECH(I,1)	I5	Node number of specified water recharge node
	IRECH(I,2)	I5	Schedule number for the water recharge node
32	NWELL	I5	Number of well nodes
Line 33 is entered only if NWELL > 0 and is repeated NWELL times			
33	IWELL(I,1)	I5	Node number of specified well node I
	IWELL(I,2)	I5	Water pumping schedule for well node I
	IWELL(I,3)	I5	Oil pumping schedule for well node I

Line	Variable	Format	Description
	RMESH(I)	F10.4	Maximum mesh spacing for well I
	ZWELL(I)	F10.4	Screen bottom elevation for well I
	ZPUMP(I)	F10.4	Pump water intake elevation for well I
0	BLANK LINE		
34	NSCHS	I5	Number of schedules

Line 35 is entered only if NSCHS > 0 and repeated NSCHS times;
For each block, line 35A is entered once and 35B is repeated NSCHS-1 times

35A	NSUB(I)	I5	Number of subscheles in schedule I
	SCH(I,1,1)	F10.4	Starting time of the first subschedule
	SCH(I,1,2)	F10.4	Value of the first subschedule
35B	SCH(I,J,1)	5X,F10.4	Starting time of subschedule J
	SCH(I,J,2)	F10.4	Value of subschedule J
0	BLANK LINE		
36	NPRINT	I5	Number of printout locations

Line 37 is entered if NPRINT > 0 and is repeated NPRINT times

37	XPRIN(I)	F10.4	X-coordinate of I-th printout location
	YPRIN(I)	F10.4	Y-coordinate of I-th printout location

_____ END OF INPUT DATA _____

Appendix D Specifications for *.VAL Files

This ASCII file contains the definition of all Nodal variables.

Line no.	Variable name	Format	Description
1	TITLE$	A80	File heading and directory string for corresponding .ARM file
2	LABEL$	A80	Column headings
3	XCOORD(I)	F13.2,1X	X coordinate of Node I
	YCOORD(I)	F13.2,1X	Y coordinate of Node I
	ZBOT(I)	F8.2	Aquifer bottom elevation at Node I
	NPROP(I)	I4	Soil type index at Node I
	NRECH(I)	I4,1X	Recharge index at Node I
	Z_{aw}(I)	F8.2,1X	Water table potentiometric surface elevation at Node I
	H_o(I)	F8.2,1X	Hydrocarbon thickness at Node I
	ρ_{ro}(I)	F8.2	Hydrocarbon density (relative to water) at Node I
4... NNOD+2	Repeat line 3, NNOD-1 times (all nodes)		

**Note: Nodes must appear in the same order as the corresponding *.MSH file.

Index

T

U

V

W

Z

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Company	Phone
Title	Extension
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City	email
State ZIP/Postal Code	Country
File Name(s)	
File Description(s)	

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What to do:

1. Please fill this report out completely: the more information we get the easier it is to fix problems. For any hardware, be sure you specify the make and model of the peripheral.
2. In the problem description section, please describe the problem in as much detail as you can. We need to try and recreate the problem, so let us know the sequence of events that led up to it. If you supply us with printed or disk copies of you Config.sys and Autoexec.bat files, then we will be able to better locate system incompatibilities. Also, with Windows® there is a utility called msd.exe that can be run to give us your system information. You can send us the printout from msd or use the tellme.exe utility available on our electronic bulletin board.
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Network Software/Version

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Hard Disk Space/Space Available

List All Other Installed Hardware

Problem Description

Please list any materials enclosed

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